Resonance phenomena in the disintegration of fluorine by protons

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1. Introduction

The bombardment of fluorine with protons gives rise to a strong emission of $\gamma$-radiation of quantum energy about $6.0 \times 10^6$ eV. The excitation function for this process shows a series of sharp resonances for proton energies up to about $2 \times 10^6$ eV (Hafstad, Heydenburg and Tuve 1936; Bernet, Herb and Parkinson 1938; Curran, Dee and Petřžílka 1938). If the $\gamma$-rays are attributed to a simple capture process according to the scheme

$$^{19}\text{F} + ^1\text{H} \rightarrow ^{20}\text{Ne}^* \rightarrow ^{20}\text{Ne} + h\nu,$$

the maximum quantum energy of the $\gamma$-radiation would be $13.1 \times 10^6$ eV according to accepted mass values, whereas measurements of the $\gamma$-ray spectrum show the presence of only one line of energy between $6.0$ and $6.5 \times 10^6$ eV (Delsasso, Fowler and Lauritsen 1937; Dee, Curran and Strothers 1939). This discrepancy might be explained in several ways:

(1) The $\gamma$-ray emission from the excited state of $^{20}\text{Ne}$ formed as the compound nucleus in reaction (1) might occur by the successive emission of two quanta, each of energy about $6.5 \times 10^6$ eV.

(2) The emission of a single $\gamma$-ray quantum of energy $6.5 \times 10^6$ eV might result in the formation of a less excited Ne nucleus which might then disintegrate into $^{16}\text{O}$ and an $\alpha$-particle.

(3) The emission of an $\alpha$-particle of about $1.5 \times 10^6$ eV energy might precede the emission of a $\gamma$-ray, the latter arising from the de-excitation of the $^{16}\text{O}^*$ nucleus left after the emission of the $\alpha$-particle of low energy, according to the reaction

$$^{19}\text{F} + ^1\text{H} \rightarrow ^{20}\text{Ne}^* \rightarrow ^{16}\text{O}^* + ^4\text{He},$$

$$^{16}\text{O}^* \rightarrow ^{16}\text{O} + h\nu.$$  

† The symbol $^{20}\text{Ne}^*$ used in this paper denotes a $^{20}\text{Ne}$ nucleus in an excited state.
Each of these mechanisms is in accordance with the observed resonance character of the $\gamma$-radiation, since in each case the de-excitation of the excited $^{20}\text{Ne}$ nucleus takes place by means of a process with a relatively long lifetime, so that the resonance levels for the proton capture are sharp. Explanations (1) and (2), however, have been shown by Dee et al. (1939) to be inconsistent with experimental facts. According to scheme (1) coincident counts should be observed in a pair of Geiger counters exposed to the radiation, and experimentally less than 1% of the expected number of coincidences is recorded under these circumstances. Schemes (1) and (2) also require the $\gamma$-ray energy to be different at successive resonance levels, owing to the increase in the energy of the bombarding protons. Dee, Curran and Strothers, however, find that the energy of the $\gamma$-rays corresponding to the resonances at proton energies of 0.33, 0.67 and 0.86 $\times 10^6\text{eV}$ is exactly the same to within the experimental error of 0.05 $\times 10^6\text{eV}$. These authors therefore conclude that scheme (3) is correct.

According to scheme (3) it should be possible to observe the emission of $\alpha$-particles of low energy exhibiting the same resonance characteristics as the $\gamma$-radiation. $\alpha$-Particles of range 0.8 cm. showing these resonance characteristics have been observed by Maclean, Becker, Fowler and Lauritsen (1939) and Burcham and Smith (1939) for the lowest resonance, occurring at a proton energy of 0.33 $\times 10^6\text{eV}$. A similar emission of $\alpha$-particles with resonance characteristics would be expected for the other resonance levels, but the observation of such particles corresponding to higher proton energies is made difficult by the fact that for proton energies above 0.4 $\times 10^6\text{eV}$ the range of the scattered protons is greater than that of the short range $\alpha$-particles. In order to investigate the emission of $\alpha$-particles at the higher resonance levels, we have separated the $\alpha$-particles from the scattered protons by a magnetic resolution method. The results of these experiments, which are described below, give very strong confirmation to mechanism (3).

We have also attempted to obtain further information about the mechanism which is responsible for the extreme sharpness of the observed resonance levels of $^{20}\text{Ne}$ by studying the widths of these levels carefully and by investigating the excitation function for the emission of long range $\alpha$-particles in the reaction

$$^{19}\text{F} + ^1\text{H} \rightarrow ^{16}\text{O} + ^4\text{He},$$

in which $^{16}\text{O}$ is formed directly in its ground state. The results of these experiments are described below and their bearing on the factors governing level widths is discussed in detail.
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2. The short-range α-particles

The experimental arrangement used for the investigation of the short range α-particles is shown in figure 1.

A target of barium fluoride was used of a thickness corresponding to a proton energy loss of about 0.04 MeV, which was sufficient to give a reasonable number of counts with a proton beam of about 50 μA. The magnetic analyser was evacuated by direct connexion through a flexible rubber tube to the main accelerating tube. The deflected α-particles emerged horizontally from the magnetic field through a thin cellophane window of 2 mm. stopping power. The particles were recorded by means of an ionization chamber 3 mm. deep, connected to a linear amplifier and scale of two counter.

The mean radius of curvature of alpha particles passing from the target to the ionization chamber was 30 cm. and the maximum magnetic field available with the arrangement was about 8000 G. It was not possible with this magnetic field to use semicircular focussing, but with an angle of deflexion of 50° the number of α-particles reaching the detecting system was sufficient and the separation of the short range α-particles from the scattered protons of energies up to 1 MeV was easily achieved.

The full curve in figure 2 shows the variation of the number of short range α-particles counted at a fixed setting of the analysing field and of the ionization chamber for proton bombarding energies from 0.3 to 0.95 × 10⁶ eV. The dotted curve in figure 2 shows the γ-ray resonances as observed by Curran et al. The similarity between the two curves is striking, and there can be no doubt that α-particle emission shows marked resonances which closely correspond to the known γ-ray resonances. The α-particle resonances are somewhat broad owing to the necessity of using a rather thick target to
obtain sufficient yields and also owing to the considerable energy spread in the proton beam. The range of the \( \alpha \)-particles emerging from the analyser was measured roughly by drawing the ionization chamber back at each of the chief resonance energies \( (0.33, 0.66 \text{ and } 0.87 \times 10^6 \text{eV}) \). The ranges were found to be \( 0.82, 0.92 \text{ and } 1.02 \pm 0.04 \text{ cm.} \), corresponding to energies of \( 1.53, 1.74 \text{ and } 1.93 \times 10^6 \text{eV} \). Such changes in \( \alpha \)-particle energy would have produced a quite negligible variation in the number of particles emerging from the analyser at a fixed magnetic field, and would be quite inadequate to account for the observed resonance phenomena. This was also verified by observing the change in the number of \( \alpha \)-particles counted at a fixed bombarding voltage, when the analysing field was varied; it was found that the variation in number was negligible for changes in the field of \( 15 \% \), corresponding to changes in \( \alpha \)-particle energy of \( 30 \% \). The increase of \( \alpha \)-particle energy at successive resonances by about four-fifths of the increase of the proton bombarding energy is exactly what would be expected according to scheme (3) above. This result proves conclusively that the \( \gamma \)-rays observed from the bombardment of fluorine by protons are emitted from a single excited state of \( ^{16}O \) which is left after the compound nucleus \( ^{20}\text{Ne}^* \) has emitted an \( \alpha \)-particle of low energy.
3. WIDTHS OF LEVELS

If the main contributions to the total widths of the resonance levels of $^{20}\text{Ne}$ are due to proton scattering and the emission of short range $\alpha$-particles, the widths of these levels excited by proton bombardment should increase uniformly with increasing proton energy. Since, also, according to the results of Bernet et al. (1938) the widths of levels of $^{20}\text{Ne}$ are only of the order $15 \text{ kV}$ for proton energies of about $1.4 \times 10^6 \text{ eV}$, the widths of the $^{20}\text{Ne}$ levels for proton energies less than $0.8 \times 10^6 \text{ eV}$ might be expected to be very narrow indeed, i.e. less than $1000 \text{ V}$. This width is much smaller than the "experimental width" in the experiments of Bernet et al. These experimenters find, however, small differences in the widths of the resonances for proton energies less than $0.8 \times 10^6 \text{ eV}$. Since one might expect all these resonances to be very much narrower than the "experimental width" it is of importance to examine the above mentioned variations in level width carefully. Accurate experiments have therefore been made to measure the widths of the levels at $0.67$, $0.59$ and $0.33 \times 10^6 \text{ eV}$. The apparatus used in these experiments is shown in figure 3.

The parallel beam of protons from the accelerating tube, having an energy spread of about $40 \text{ kV}$, enters a magnetic resolving field vertically at $A$. After being bent round through $90^\circ$ the protons emerge horizontally from the magnetic field, all the protons of a particular energy being focused, to the first order, at the same height, $P, P', etc$. A narrow horizontal slit, placed in the path of the horizontally emerging proton beam, selects a particular energy component of the beam. The degree of energy homogeneity in the proton beam passing through the slit is governed only by the narrowness of the slit. In the actual experiments an adjustable water-cooled slit was used consisting of two equal cylindrical tubes, with their axes accurately parallel, which
could be rotated about an axis mid-way between and parallel to the two cylinders. The slit width used in the experiments was about 0.5 mm., corresponding to an energy spread of only 0.6%, i.e. about 4 kV at $0.7 \times 10^6$ eV mean energy. Relative measurements of proton energies were made by measuring the relative strengths of the magnetic fields used to deflect the protons. Small changes in the magnet current were taken as proportional to small changes of proton energy, and over the small range of energy covered by each resonance level the error introduced by this assumption was negligible. An absolute calibration of the magnet current reading in terms of the voltage scale was made in subsidiary experiments. The $\gamma$-rays were detected by a pair of Geiger counters as in the experiments of Curran et al. (1938).

The results of measurements for two resonances with this arrangement are shown in figure 4. The $\gamma$-ray intensities are expressed in arbitrary units and the absolute values of proton energy are liable to an error of about 7 kV. The width of the resonance at $0.33 \times 10^6$ eV is only about 6 kV. The "tail" at the high-energy side is due to some slight non-uniformity of target thickness. The resonance at a proton energy of $0.67 \times 10^6$ eV shows a half-width of practically the same value as that at $0.33 \times 10^6$ eV, and we believe that in both cases the width is determined by experimental resolving power. The
"experimental" widths given by Bernet et al. for these levels are 9.8 and 15.7 kV and our results suggest that these variations of width are not due to variations in the real level width, but that the latter are in fact considerably smaller than the "experimental" width.

The half width of the resonance at 0.59 x 10^6 eV proton energy is, however, about 35 kV, which is considerably larger than the "experimental" width. The resonance shows no sign of being composed of a closely spaced doublet and it is improbable that more than two levels exist with such small spacing. It therefore appears probable that the factors contributing to the width of this level are different from those effective at other resonances, and it was thought that some singularity might be observed in the emission of long range α-particles from the excited 20Ne nucleus in accordance with reaction (3) in the energy region occupied by the broad resonance level. A study of the excitation function of this group of α-particles was therefore made.

4. Excitation function for the long-range α-particles

In order to study the excitation function of the 5.9 cm. α-particles emitted in the reaction

\[ ^{19}F + ^{1}H \rightarrow ^{16}O + ^{4}He, \]  

in detail, it was necessary again to use the resolving slit in order to improve the homogeneity of the ion beam, and the experimental arrangement was exactly that used in the γ-ray experiments (see figure 4). The target was a thin deposit of barium fluoride corresponding in thickness to a proton energy loss of about 10 KeV. The proton beam was limited by stops so as to bombard a fixed spot of the target about 3 mm. diameter. The proton current to the target did not change by more than about 2% during bombardment at a particular voltage and magnetic field. The effective stopping power of air and mica between the target and the ionization chamber used for detection of the α-particles was about 1.5 cm. less than their mean range. The cut off bias on the counter was set so that all α-particles passing through the ionization chamber were recorded. The difference in counting rate with and without a γ-ray source of several millicuries near the ionization chamber was measured and found to be negligible and it is therefore certain that the presence of intense γ-radiation at the resonance energies had no effect on the counting of the α-particles. The excitation function of the long range α-particles for proton energies of 0.55 to 1.0 x 10^6 eV is shown in figure 5.

This excitation function exhibits the familiar rise in the cross-section for the process with increasing proton energy. It appears, however, that
superposed upon this background are two maxima, apparently of a resonance nature. The most marked of these maxima is at a proton energy of \(0.83 \times 10^6\) eV and the less distinct one at about \(0.72 \times 10^6\) eV.

In order to ascertain definitely whether or not the maxima in the excitation function for the long range \(\alpha\)-particle occur at the same proton energies as resonances for \(\gamma\)-ray emission, excitation functions for both long range \(\alpha\)-particles and \(\gamma\)-ray emissions were observed simultaneously. The \(\gamma\)-rays were detected by means of a pair of Geiger counters, as in previous experiments. The results of these experiments are also shown in figure 5, and it appears quite clear that the anomalies in the excitation function for the long range \(\alpha\)-particles do not occur at the same energies as the resonances for \(\gamma\)-ray emission. The investigation of the excitation function using thin targets and a highly homogeneous proton beam is made difficult for proton energies less than \(0.55 \times 10^6\) eV by the small yield of the reaction.

An estimate has been made of the relative number of long range (5.9 cm.) and short range (1.0 cm.) \(\alpha\)-particles emitted at a proton energy of about 0.87 MeV. With a target of "thickness" about 10 keV the number of short range \(\alpha\)-particles was about 100 times that of long range \(\alpha\)-particles.
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5. Discussion

The experimentally observed facts concerning the disintegration of fluorine by protons may be summarized as follows:

(i) There is an emission of $6.2 \times 10^6$ eV $\gamma$-rays with resonant characteristics and an emission of short range $\alpha$-particles with the same excitation function.

(ii) Most of the observed resonance levels for $\gamma$-ray emission are sharp (less than 6 kV half width) but that at $0.59 \times 10^6$ eV has a width of 35 kV.

(iii) The excitation function of the long range $\alpha$-particles exhibits resonant features which do not appear to be associated with the $\gamma$-ray resonances.

In order to explain these facts it is first necessary to find some mechanism which is responsible for the extreme sharpness of most of the observed $\gamma$-ray resonances, i.e. for the comparatively long lifetime of the levels of the excited $^{20}$Ne nucleus formed by the capture of a proton by the $^{19}$F nucleus. The widths of the energy levels of the excited $^{20}$Ne are determined by the various possible ways in which this nucleus can lose its energy of excitation. The possibilities are:

(i) Resonance scattering of the protons.

(ii) Emission of a short range $\alpha$-particle and formation of $^{16}$O in an excited state.

(iii) Emission of a long range $\alpha$-particle and formation of $^{16}$O in the ground state.

(iv) Direct transition to the ground state of $^{20}$Ne by the emission of a $\gamma$-ray. This does not occur with any measurable intensity.

The contributions to the level widths due to (i) and (ii) are small owing to the low penetrability of the Coulomb barrier of $^{20}$Ne* for protons and $\alpha$-particles of the energies considered, and the contribution due to the possibility of $\gamma$-ray emission to the ground state is negligible owing to the long lifetime of $\gamma$-ray processes. Process (iii) however is accompanied by the release of about $8 \times 10^6$ eV energy and this would normally give rise to a level width of the order of $1 \times 10^6$ eV. In order to explain the observed sharpness of the levels of $^{20}$Ne responsible for the short range $\alpha$-particle resonances it is necessary to assume that the emission of an $\alpha$-particle with full energy is either completely forbidden by a rigid selection rule or is made improbable by the operation of some other selection rule which reduces the probability of its emission by a factor of the order of 1000 at least. The long range $\alpha$-particles would be expected to arise from another set of levels of $^{20}$Ne of width about $1 \times 10^6$ eV which would overlap to such an extent as to render
the excitation function for the long range \( \alpha \)-particles a gradually rising curve of the usual type.

This picture does not account for the broadness of the level at \( 0.59 \times 10^6 \text{ eV} \). This might be due to the fact that the emission of an \( \alpha \)-particle of full energy leaving an \( ^{16}\text{O} \) nucleus in the ground state is not totally forbidden in this case, but is only made less probable by the operation of some less rigid selection rule. If selection rules of this type exist, then it is not possible to assume that the width of each level of \( ^{20}\text{Ne} \) which can dissociate into a long range \( \alpha \)-particle and an unexcited \( ^{16}\text{O} \) nucleus is of the order of \( 1 \times 10^6 \text{ eV} \). Levels of \( ^{20}\text{Ne} \) with much smaller half widths might exist and the existence of such levels would give rise to resonant features in the excitation function of the long range \( \alpha \)-particles. Some such mechanism is probably responsible for the resonances observed in this excitation function although there is no evidence that such a resonance occurs at \( 0.59 \times 10^6 \text{ eV} \).

6. Selection rules and intensities

Some information as to the nature of the selection rules governing the break up of \( ^{20}\text{Ne}^* \) can be obtained from a consideration of the momenta changes in the processes. It has been pointed out by Bethe (1937) and by Breit (see discussion in Bernet et al. 1938) that since the wave functions of both \( ^{16}\text{O} \) and \( ^4\text{He} \) have even parity (i.e. do not change in sign when the internal co-ordinates of the constituent particles are reversed), and also since both nuclei have zero spin in the ground state, the parity of any compound system formed by the two particles is even or odd according as the orbital angular momentum is even or odd. If then the nucleus \( ^{20}\text{Ne} \) is formed in an excited state with even spin and odd parity or with odd spin and even parity, such a compound nucleus will be unable to split up into an \( \alpha \)-particle and an \( ^{16}\text{O} \) nucleus in the ground state. This rigid selection rule provides a simple explanation of the sharp resonances observed in the emission of the short range \( \alpha \)-particles and the subsequent \( \gamma \)-rays.

The large yield of \( \gamma \)-rays\(^\dagger \) from the reaction suggests that for the resonances at the lower proton energies the compound \( ^{20}\text{Ne}^* \) nuclei are produced by the component of the proton beam with zero orbital momentum. Assuming this to be the case the following two schemes (table 1) can be obtained for the parity and spin of \( ^{20}\text{Ne}^* \), according as one assumes the parity of \( ^{19}\text{F} \) to be even (a) or odd (b).

\(^\dagger\) The \( \gamma \)-ray intensity at 860 kV is of the order of 10 millieuries for 100\( \mu \)A proton current.
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Table 1

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<td>$^{20}$Ne*</td>
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<td></td>
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<tr>
<td>$^{20}$Ne*</td>
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<td>$^{20}$Ne*</td>
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It can be seen that on either assumption as to the parity of $^{19}$F, two types of compound $^{20}$Ne* nucleus can be formed, first the type $a$ (1) and $b$ (2) which can disintegrate into normal $^{16}$O and an $\alpha$-particle, and secondly the type $a$ (2) and $b$ (1) for which this transition is forbidden, since the parity and spin are of opposite sign. Each of these types of $^{20}$Ne* might however disintegrate into an excited $^{16}$O nucleus and an $\alpha$-particle and table 2 shows the possible schemes for the changes of spin and parity in this case, assuming the parity of the excited $^{16}$O to be odd. It is clear from this table that the states of $^{20}$Ne* which can emit a long range $\alpha$-particle ($a$ (1) and $b$ (2)) lead to an excited $^{16}$O nucleus with odd spin, whereas the states which can only emit a short range $\alpha$-particle ($a$ (2) and $b$ (1)) lead to an excited $^{16}$O with even spin. Thus the two types of $^{20}$Ne* cannot both emit a short range $\alpha$-particle and also leave the same excited $^{16}$O. It follows that when the emission of long range $\alpha$-particles is allowed, the emission of short range $\alpha$-particles can only occur if it involves a level of $^{16}$O* different from the $6 \times 10^6$ eV level involved when the long range $\alpha$-particle emission is completely forbidden.

A similar conclusion follows if it is assumed that the excited $^{16}$O nucleus has even parity. It is thus impossible to account for the broad resonance at
0.59 \times 10^6 \text{ eV} \text{ proton energy in terms of competition by a partially forbidden long range } \alpha \text{-particle unless it is assumed that more than one excited level of } ^{16}\text{O is involved. This applies also to the weak resonances in the region } 1.0 \text{ to } 1.5 \times 10^6 \text{ eV proton energy found by Bernet, Herb and Parkinson.}

It is not possible to obtain any precise information about the spin or parity of the excited level of } ^{16}\text{O involved in the process from the fact that a } \gamma \text{-ray transition occurs between this level and the ground state. For levels of } ^{16}\text{O with excitation energy of about } 6 \times 10^6 \text{ eV, no process other than } \gamma \text{-radiation is energetically possible. Therefore, even if the } \gamma \text{-ray transition is one involving no change in parity and a spin change of unity (a transition for which electrical dipole and quadripole radiation are forbidden) magnetic dipole radiation would still occur in the absence of any competing process. The transition between two levels of zero spin is completely forbidden, except by total internal conversion, and this selection rule implies that the spin of the excited state of } ^{16}\text{O at } 6 \times 10^6 \text{ eV is different from zero.}

The number of disintegrations occurring in a target of thickness } \Lambda \text{ (expressed as the energy loss of the proton beam in passing through it) bombarded with } N \text{ protons is } \phi \Lambda \sigma_E N \text{ where } \phi \text{ is a factor involving the number of nuclei in the target and } \sigma_E \text{ is the cross-section for the process at a proton energy } E. \text{ It is assumed that in this case the cross-section is roughly constant in the energy range } E \pm \Lambda. \text{ In the case of a resonance disintegration for which the width of the resonance } \Gamma_r \text{ is small compared with } \Lambda \text{ the yield from the reaction when the proton energy } E \text{ is equal to the resonance energy } E_r \text{ is approximately } \phi \Gamma_r \sigma_{E r} N \text{ where } \sigma_{E r} \text{ is the cross section for the process when } E = E_r. \text{ The values of } \sigma_E, \sigma_{E r} \text{ in the case of emission of long and short range } \alpha \text{-particles in the bombardment of } ^{19}\text{F by protons are given by the Breit-Wigner dispersion formula as follows:}

\begin{align*}
\sigma_E &\approx \lambda^2 (\Gamma_p \Gamma_\alpha/\Gamma_p^2) (\Gamma_\alpha/d), \\
\sigma_{E r} &\approx \lambda^2 (\Gamma_p \Gamma_r/\Gamma_p^2),
\end{align*}

where } \Gamma_p \text{ is the width of the level of } ^{20}\text{Ne for proton emission, } \Gamma_\alpha \text{ that for long range } \alpha \text{-particle emission, } \lambda \text{ is the quantum wave-length of the incident protons, and } d \text{ is the distance between the levels which can emit long range } \alpha \text{-particles. It is assumed that } \Gamma_p \ll \Gamma_\alpha \text{ and the factor } \Gamma_\alpha/d \text{ in } (5) \text{ allows for the overlapping of the broad levels which can emit long range } \alpha \text{-particles. By substituting these expressions in the formulae for the number of disintegrations we obtain for the ratio of the intensities of short range } \alpha \text{-particles to long range particles the value } d/\Lambda. \text{ If it is assumed that } d \text{ is the same as for the levels which can emit short range } \alpha \text{-particles (about } 0.1 \times 10^6 \text{ eV) we obtain for this ratio the value of } 10. \text{ The experimental value is about } 100
and the most plausible explanation of this discrepancy is that the value of $\Gamma_p$ is different in (5) and (6). Such a difference would be present if the angular momentum of the incident proton were different in the two cases; it should be possible to obtain information on this point by an investigation of the anomalous scattering of protons in fluorine.

If it is assumed that the resonances in the excitation function for the long range $\alpha$-particles are in fact due to states of $^{20}\text{Ne}$ for which the emission of a long range $\alpha$-particle is only partially forbidden, then it is possible to calculate a theoretical value for the ratio of the number of resonant to the number of non-resonant long range particles. This ratio is again $d/A$ if it is assumed that the width for long range $\alpha$-particle emission at resonance $\Gamma_\alpha$ is large compared with $\Gamma_p$; or $\Gamma_\alpha/\Gamma_p \cdot d/A$ if one assumes that $\Gamma_p \gg \Gamma_\alpha$. The value of $d/A$ is about 10 whereas the experimental ratio is about $\frac{1}{4}$. This suggests either that $\Gamma_\alpha$ is in fact much smaller than $\Gamma_p$ (i.e. the partial selection rule must make long range $\alpha$-particle emission improbable by a factor of about 10,000) or alternatively that $\Gamma_p$ is smaller for the levels of $^{20}\text{Ne}$ which show resonance for long range $\alpha$-particle emission than for those showing no resonances. If this latter alternative is the correct one it would imply an orbital momentum of the proton in this case larger than 1 and in such circumstances the resonance in the long range $\alpha$-particle emission might be attributed to the $\alpha$-particle leaving the $^{16}\text{O}$ nucleus with a large orbital momentum. In any case it seems safe to conclude that protons with angular momentum different from zero must be responsible for at least one mode of disintegration of $^{20}\text{Ne}^\ast$ into $^{16}\text{O}$ and an $\alpha$-particle. The correctness of this conclusion could be tested by studying the angular distribution of the disintegration products. A partial selection rule of the type necessary to give resonant long range $\alpha$-particle emission has already been proposed on the basis of separate conservation of orbital and spin momenta. Recent measurements of the quadripole moment of the deuteron, however (Kellog, Rabi, Ramsey and Zacharias 1939) indicate that in nuclear systems the interaction of spin and orbital momenta is very large, and it does not seem likely that the probability of emission of a long range $\alpha$-particle can be reduced by a factor of 100 or more by the operation of such a weak selection rule.

The only other example of resonance in the emission of long range $\alpha$-particles under proton bombardment is in the case of boron, where the excitation function shows a sharp resonance at a proton energy of about $0.17 \times 10^6$ eV (Williams, Wells, Tate and Hill 1937; Bowersox 1939). In this case, however, a resonance in the emission of $\gamma$-rays seems to occur at precisely the same energy as the $\alpha$-particle resonance, and, further, the short range $\alpha$-particles emitted in the transmutation show no resonant features.
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It seems then that the same mechanism is not responsible for the resonance effects in the two cases. Investigations of the excitation functions of other transmutations are being carried out, but it is not necessarily to be expected that resonant phenomena for high energy particles are in any way general.

This work was carried out in the Cavendish High Voltage laboratory. We wish to thank Mr P. I. Dee for his interest in the work, and Messrs Heitler, Kahn and Peierls for their comments on the theoretical aspects of the problem.

Summary

An investigation has been made of the short range $\alpha$-particles emitted from fluorine under proton bombardment. The $\alpha$-particles were separated from the scattered protons by magnetic deflexion. The results confirm the view that the resonant $\gamma$-radiation is emitted from an excited level of $^{16}$O formed after emission of a low energy $\alpha$-particle. A description is given of some measurements of the widths of the resonances for $\gamma$-radiation, using magnetically resolved beams of protons of high homogeneity. The results indicate that the resonances are very narrow in two cases examined, and considerably broader in the third. The excitation function for the emission of 5-9 cm. $\alpha$-particles in the reaction $^{19}$F + $^1$H $\rightarrow$ $^{16}$O + $^4$He has been examined carefully. The excitation function shows resonant features superposed upon a background which increases with increasing proton energy. A discussion of some possible explanations of the resonant phenomena observed is given.

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