The Scattering of Alpha-Particles by Argon, Oxygen and Neon*

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Data on the scattering of alpha-particles by argon, oxygen and neon have been obtained with a novel experimental arrangement developed for the purpose. Anomalies were found in the scattering by all three elements. Irregularities in the course of the anomalies in the cases of oxygen and neon have been interpreted as resonance phenomena. Estimates of the radii of the various nuclear barriers, based on the assumption that the penetrability of the barrier is appreciable at the lowest energy for which an anomaly is apparent, give the values $4.5(10^{-13})$ cm for O^{16}, $4.6(10^{-13})$ cm for Ne^{20}, and $7.5(10^{-13})$ cm for A^{40}. The first two are lower than values calculated from the formula $R=2.05(10^{-13})A^{\frac{1}{3}}$ and the last is somewhat higher. The latter result agrees with deductions of Pollard, Schultz, and Brubaker from data on the A-α-n reaction.

INTRODUCTION

THE scattering of alpha-particles by the gases argon, oxygen and neon has been investigated to some extent by Rutherford and Chadwick[1] and by Riezler.[2] Rutherford and Chadwick found that the number of particles scattered by argon agreed closely with the number calculated from the geometry of the apparatus, under the assumption of inverse square forces, up to 7.3 Mev alpha-particle energy in the angular range 40°–50° and 8.4 Mev in the range 29°–44°. Riezler found that argon and neon scattered classically into the angular range 55°–90° for energies as high as 5.2 Mev. For oxygen he found an anomaly in the scattering consisting of a decrease in numbers scattered below the classical value, beginning at 4.6 Mev. From his results Riezler estimated the radius of the oxygen potential barrier to be $4.5(10^{-13})$ cm and that of the neon barrier to be less than $4.6(10^{-13})$ cm.

The present work was undertaken to extend the data on alpha-particle scattering by these three gases to higher alpha-particle energies and other angles of scattering. In the case of argon, the discovery by Pollard, Schultz and Brubaker[3] that neutrons are emitted from argon under bombardment by alpha-particles of energy as low as 4.5 Mev, and the deduction that the nuclear radius of argon is exceptionally large, made it seem likely that anomalies in the scattering of alpha-particles by argon might exist at lower energies than previously suspected.

A novel experimental arrangement, in which the scattered particles were detected by two proportional counters of toroidal shape developed for the purpose, was used for the work. The scattering into four ranges of angles, whose mean angles were approximately 53°, 65°, 89° and 104°, was investigated with Ra C′, and in some cases Th C′, alpha-particles. In the case of oxygen some data were obtained on the scattering into a third range of angles, of mean angle 78°.

Anomalies were found in the scattering by all three elements. The number of particles scattered by argon was found to decrease below the classical value at the higher energies, the decrease beginning at lower energies and being more marked at the higher angles. Irregularities were found in the anomalies in scattering by oxygen and neon which are explainable as reasonance phenomena. Estimates of the various nuclear radii were made from the results.

APPARATUS

The apparatus used in the experiments, a cross section of which is shown in Fig. 1, differed considerably from the usual "annular ring" arrangement. The incident beam of particles was defined by a circular aperture in front of the source disk, and the scattered particles were detected by proportional counters of toroidal

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[1] E. Rutherford and J. Chadwick, Phil. Mag. 4, 605 (1927).
[2] W. Riezler, Ann. d. Physik 23, 198 (1935).
[3] E. Pollard, H. L. Schultz and G. Brubaker, Phys. Rev. 53, 351 (1938).

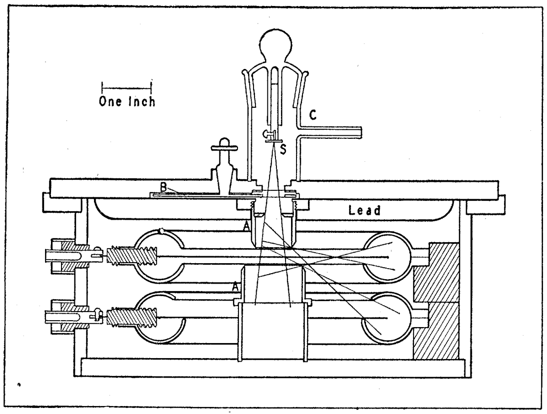

FIG. 1. Cross section of scattering chamber and counters.

shape. The beam of scattered particles was defined by the beveled ends of the brass tubes, *A*,*A* and the edges of the openings in the counters. The use of two counters, mounted one above the other, made it possible to count particles scattered into two angular ranges simultaneously. Two sets of tubes *A*,*A* of different lengths were used to investigate the scattering into four ranges of angles. The counters were contained in a cylindrical chamber on top of which was mounted a short glass tube which contained the source disk. Chamber and tube were separated by a thin foil. The chamber was filled to a pressure of ten cm with the gas being investigated.

The type of counter which was developed for this work consisted of a hollow toroid of aluminum (large radius, 5.2 cm; small radius, 1.0 cm) inside of which was supported a circular loop of ten-mil wire. Details of the counter and of the supports for the wire are shown in Fig. 2. The aluminum toroid, which formed the negative electrode of the counter, was constructed in two parts, a top and a bottom half-shell, for ease in construction and assembly. Through the peripheral flange of the toroid passed amber plugs, fitted with grounded guard sleeves, which served as insulating supports for the wire. The two ends of the wire, which led to the input of an amplifier, passed to the outside of the toroid through one of the amber insulators. Particles to be counted entered the counter through a slot in the toroid, as indicated in Fig. 1.

Two of these counters, with the entrance slots in different places, were mounted on hard rubber blocks in the scattering chamber and the wire of each connected to a separate amplifying and recording system. The amplifiers used consisted of three stages, resistance-capacity coupled, having a total amplification factor of about 50,000. The third stage operated a single thyratron recording circuit. This type of circuit was sufficiently fast since seldom did the counting rate approach sixty per minute.

Since the counters had no foils over their entrance slots, they were filled with the gas in the scattering chamber to a pressure of ten cm. Under these conditions they were found to operate quite satisfactorily as proportional counters for alpha-particles. As in all such counters the negative voltage applied to the toroids was not critical; the value to be used depended upon the sensitivity of the associated amplifier. As is to be expected from the various lengths and directions of possible paths of particles through the counter, the resultant impulses were not uniform. They varied in height, as measured by a cathode-ray oscillograph, from twice to about eight times the height of the background due to gamma-rays. This relatively large ratio of heights of background to impulse is thought to have been caused by the considerable length of the counter and the large solid angle which it subtended at the alpha-particle source, plus the fact that photoelectrons are able to pass parallel to the wire while the alpha-particle paths are perpendicular to the wire. Little difference was apparent in the operation of the counter when filled with different gases, except as to the electrode voltage necessary.

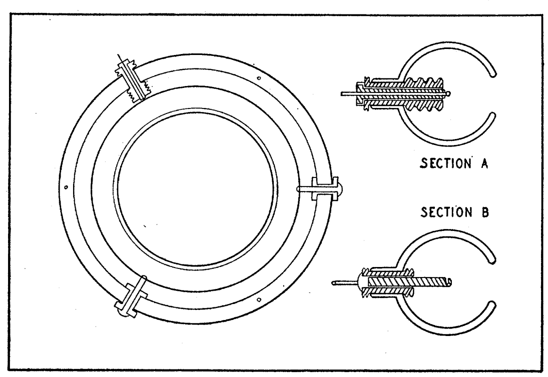

FIG. 2. Details of construction of counters. Lower shell of counter and cross sections of two insulators are shown.

The scattering chamber was a steel cylinder having a steel bottom and a brass flange around its top. Into a depression in this flange was fitted the flat brass plate which formed the top of the chamber. The joint was made airtight by stopcock grease between the flange and plate, and Apiezon putty around the edge of the plate. On the underside of the top was fastened a lead plate a little over a centimeter thick which supported the upper section of edges defining the alpha-particle beams. A disk, B, turned through a metallic ground joint, carried a set of mica foils with which the alpha-particle energy could be varied. The stopping power of the foils was determined both by weighing and by calibration with alpha-particles. The same disk served to prevent particles from entering the scattering chamber during determinations of the background count.

The hole in the center of the chamber top was covered by a thin foil. At first celluloid foils of about one mm stopping power were used, and the upper chamber connected to the lower through a long tube fitted with an adjustable leak. By the exercise of considerable care the chambers could be emptied and filled without straining the foil. However, considerable trouble was experienced with contamination of the counters in spite of glass wool filters and a liquid-air trap placed in the tube connecting the two chambers. The celluloid foils were, therefore, abandoned in favor of mica foils thick enough to withstand at least ten cm pressure and the two chambers were connected to different pumping systems.

The gas being investigated was stored in a reservoir, into which it was introduced through a liquid-air trap, under a pressure of about 25 cm when not in use. It was introduced into the evacuated scattering chamber through a capillary leak, and was removed and returned to the reservoir by a mercury pump. To eliminate the possibility of spurious results through admixture of the small amount of air left in the scattering chamber after each evacuation, fresh oxygen and argon were placed in the reservoir after each five or six runs. In the case of neon a charcoal trap immersed in liquid air was used to speed and make more complete the evacuation.

For most of the work the alpha-particles of Ra C′ were used, although some work was done with Th C′ sources. The Ra C′ sources were prepared by exposing charged disks, nine mm in diameter, to radon. The strength of the sources was measured by counting the alpha-particles emitted into a small solid angle normal to the disks.

Experimental Method and Treatment of Data

After a source disk had been placed in the apparatus and the chamber filled with gas, a series of five minute counting periods, including at least two with each available alpha-particle energy and at least three background counts, were taken. This procedure was repeated with subsequent sources until a number of particles ranging from about four hundred in the case of the larger angles to several thousand at the smaller angles had been counted. These data were reduced to the average number of particles scattered into the counter per minute per millicurie source strength for each incident alpha-particle energy, and a plot made of these numbers against energy.

It is known from the experiments of Rutherford and Chadwick[1] and of Riezler[2] that argon scatters alpha-particles of energies below about five Mev through the angles investigated in this work according to the Rutherford-Darwin law. A curve of $1/E^2$ against E should therefore fit the experimental curve of number against energy for argon up to $E=5$ Mev. Such a curve was fitted to the experimental points. Deviations of the points from the curve at energies above five Mev then indicated departure from classical scattering. By use of this theoretical curve and the Rutherford-Darwin formula similar curves applying to oxygen and neon were constructed. Deviations of the experimental points for each gas from the corresponding theoretical curve indicated departures from classical scattering. The results were finally exhibited as plots of the ratio of observed to classically expected numbers against the energy of the alpha-particles. These curves are shown in Figs. 4, 5 and 6. The lengths of the vertical lines through the experimental points, intended to indicate the relative probable errors of the points, were obtained by dividing the ordinate of the point by the square root of the number of particles counted.

Angular Conditions

Four different angular ranges were investigated in the case of each gas except oxygen, for which a fifth range was investigated. The ranges were quite large and somewhat overlapping. The extent of overlap is indicated by the histograms of Fig. 3, which indicate the angular distributions of detectable scattered particles which would exist if the particles were classically scattered. The histograms were derived by dividing the source disk and scattering volume into small sections and calculating the relative number of scattered particles associated with each pair of sections in source disk and scattering volume which would enter a small section of the counter aperture. The appropriate angle of scattering was also calculated. The total area in each histogram is proportional to the experimental number of alpha-particles of 2.5 Mev energy scattered by argon per minute per millicurie into that range of angles. The average angles of scattering given in Figs. 4, 5 and 6 are derived from the histograms. These average angles are 53°, 65° 30′, 88° 45′ and 104°.

Experimental Results

Argon

An anomaly in the scattering by argon in the form of a decrease below the classically expected number was observed (Fig. 4). The decrease persists to the highest energies used. At the smallest angles (mean 53°) the least energy for which the anomaly is apparent is about 6.5 Mev. This least energy decreases as the angle of scattering is increased, being about five Mev at the highest angles for which observations were taken.

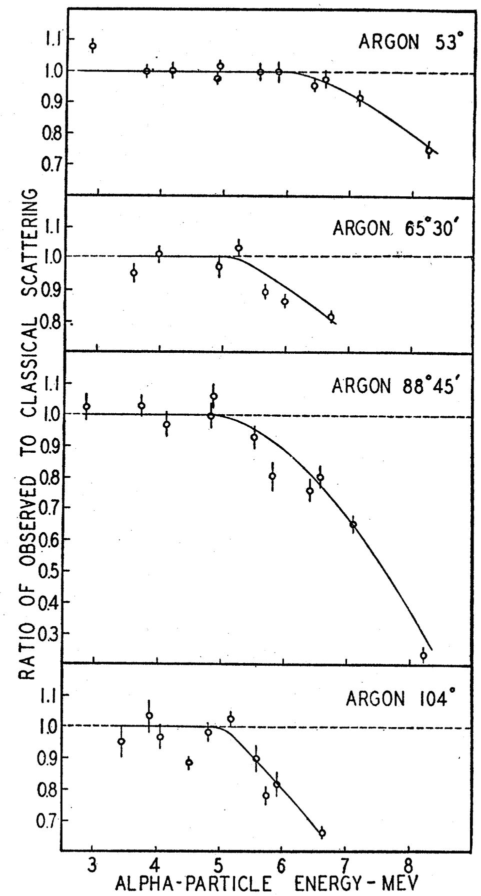

Fig. 4. Experimental results for argon.

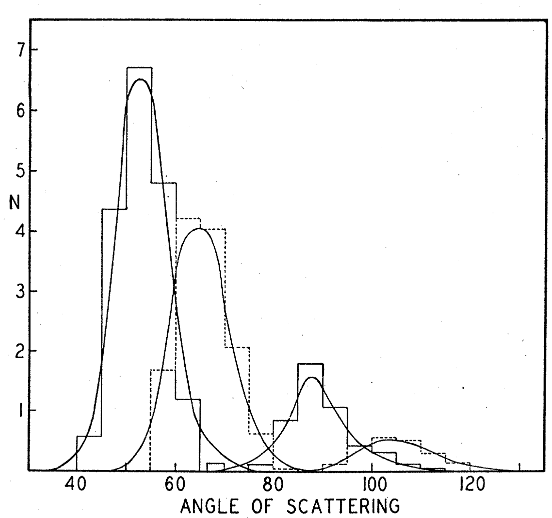

Fig. 3. Calculated angular distribution of detectable scattered particles on assumption of Coulomb forces. Distributions for the four angular ranges whose mean angles are 55°, 65° 30′, 88° 45′ and 104° are shown.

An apparent anomaly of this type would be caused if fast alpha-particles produced impulses only as high as, or a little higher than, the impulses of the gamma-ray background, not large enough to be recorded. That the observed decrease was not due to this cause was shown in the following way. First, the counting level was lowered until some of the background impulses were being counted, but no increase in the net count was observed. Second, a cylindrical foil was placed in front of the counter openings to reduce the energy of the particles entering.

Failure again to observe an increased net count showed that the counters were responding properly to fast alpha-particles.

The character of the anomaly observed makes it likely that it is caused by penetration through the top of the argon potential barrier. If we assume that this is true, and that the penetrability of the barrier for particles of zero angular momentum becomes appreciable ($\sim$10 percent) at the minimum energy at which the anomaly becomes apparent, the Gamow probability formula leads to a radius for the argon potential barrier of about 7.5 (10^{-13}) cm. This is about eight percent higher than the radius (7.0×10^{-13} cm) calculated from Bethe's formula, $R=2.05$ (10^{-13})$A^{\frac{1}{3}}$ cm.[4]

This large radius is in agreement with the deductions of Pollard, Schultz, and Brubaker[3] concerning the A-α-n reaction. Attempts to fit their experimental yield pressure curves theoretically, based on the assumption that the emission of neutrons was governed by the penetrability of the argon barrier for alpha-particles, were successful only when a large radius was assumed for the argon barrier. That the two experiments should lead to similar estimates of the radius is apparent from the fact that the lowest energy for which neutrons were observed (4.5 Mev) is only slightly less than the minimum energy at which the scattering anomaly becomes apparent.

Oxygen

The anomalies found in the scattering by oxygen are shown in the curves of Fig. 5. At the smaller angles the anomaly consists of a decrease below the classically expected number followed by a slight rise. As the angle of scattering increases the decrease first becomes more marked, then, as the angle increases further, becomes less marked and the increase in number scattered at high energies becomes the most prominent feature of the anomaly. At the highest angles the number of scattered particles reaches five times the expected number.

The results for the mean angle 65° 30′ are in fair agreement with those of Riezler[2] who investigated the scattering of polonium alpha-particles at angles between 55° and 90°. A calculation of the radius of the oxygen potential barrier, made on the assumption that the penetrability becomes appreciable at the least energy (4.6 Mev) at which the scattering anomaly becomes apparent, leads to a value of 4.5 (10^{-13}) cm, in agreement with the estimate made by Riezler. If the radius is calculated from Bethe's formula, the result is 5.17 (10^{-13}) cm, about 15 percent higher.

In the two largest angular ranges the ratio of observed to classically expected numbers rises rapidly above unity as the energy of the alpha-particles is increased. The curves show no decrease below unity, although one may exist between four and five Mev, where no data were taken.

At about six Mev there is an irregularity in the curves. It is quite marked in the curve for the mean angle 88° 45′, although very slight in the curve for the larger angles. Since oxygen is not disintegrated by alpha-particles, and there is, consequently, no question of competition of nuclear processes, this irregularity is attributed to a resonance level. Further, because of the small abundance of the isotopes of oxygen other than O^{16}, the resonance level must be in the Ne^{20} nucleus. If the alpha-particle energy at resonance is taken to be 5.8 Mev, the resonance level is about 9.3 Mev above the ground state of Ne^{20}.

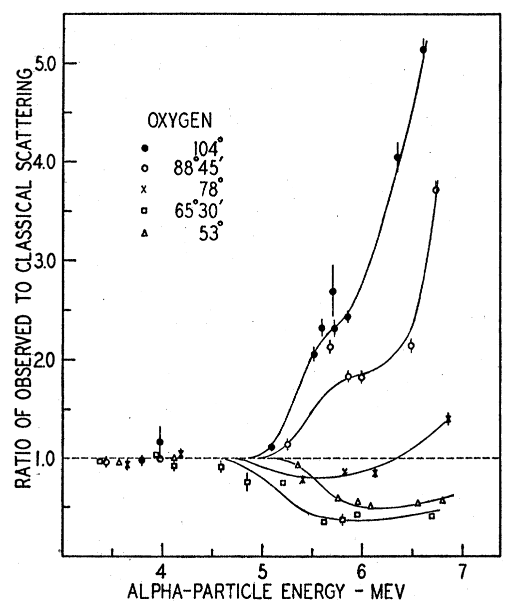

FIG. 5. Experimental results for oxygen.

[4] H. A. Bethe, Rev. Mod. Phys. 9, 172 (1937).

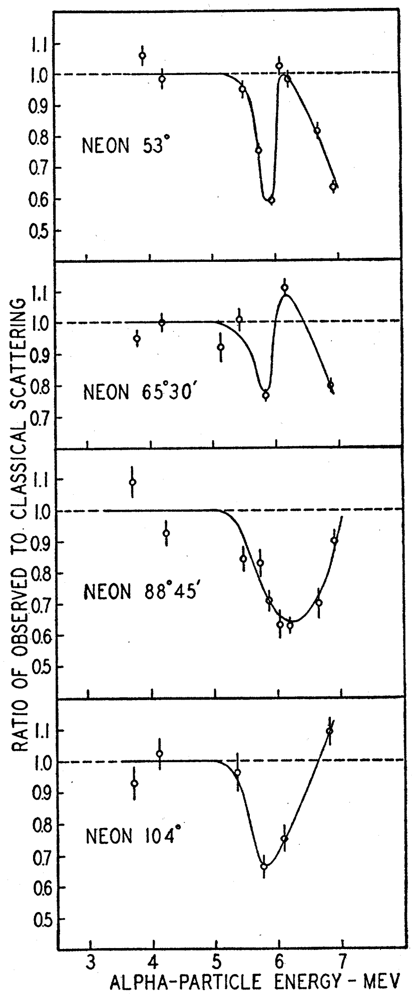

FIG. 6. Experimental results for neon.

This does not correspond to any level previously found.

Since we are dealing with scattering by an element not disintegrated by alpha-particles, we may apply the theoretical results of Wenzel.[5] According to the curves given by him, the maximum ratio of observed to classical scattering of alpha-particles of zero angular momentum and 5.7 Mev energy which can be produced by oxygen is three. Since the irregularity in the curves does not rise above the ratio three, it may be attributed to resonance scattering of particles of zero angular momentum. The subsequent rise to ratios greater than three must be attributed to particles of higher angular momentum. It is to be expected that such particles would contribute to the anomaly since the higher energies are above the top of the oxygen barrier.

Neon

The most striking feature of the results for the scattering by neon (Fig. 6) is a very sharp irregularity in the curves for the mean angles 53° and 65° 30′ which is not present in the other two curves. The irregularity consists of a decrease from unity at about 5.3 Mev to a minimum at 5.9 Mev, followed by a rapid rise to approximately unity at 6.1 Mev and a subsequent fall. For the two higher angular ranges the course of the curves is a decrease at 5.2 Mev to a minimum, followed by a rise. There is no sign of the irregularity present in the first two curves.

It was established that the peculiarities observed are not caused by protons produced by the disintegration of neon. A foil was placed in the apparatus to prevent alpha-particles, but not protons, from reaching the counters. No protons were detected.

Because of the relatively large yield of protons from neon under alpha-particle bombardment, it is not certain whether the observed irregularity is caused by a resonance level of the compound nucleus or to a rapid variation in the relative probabilities of emission of protons and alpha-particles. No data on the variation of proton yield with alpha-particle energy are available to help in deciding this question. A possible explanation of the curves for the two lower angular ranges is that the initial decrease is caused by penetration of the barrier, and that the subsequent peak at 6.1 Mev is caused by a resonance level of Mg^{24}. Because of the magnitude of the peak, it seems improbable that it could be caused by Ne^{22}, which composes ten percent of neon.

From the calculated classical angular distribution of detected particles, it may be deduced that, since no evidence of an irregularity is apparent in the curve for the mean angle 88° 45′, only particles scattered at angles less than about 75° contribute appreciably to the observed irregularity. The fact that the irregularity does not appear at all angles does not preclude its assignment to a resonance phenomenon, since, according to Mott[6] and to Bethe,[7] the magnitude

[5] P. Wenzel, Zeits. f. Physik **90**, 754 (1934).

[6] N. F. Mott, Proc. Roy. Soc. **133**, 228 (1931).

[7] H. A. Bethe, Rev. Mod. Phys. **9**, 175 (1937).

of a scattering anomaly due to a resonance level may vary rapidly with the angle of scattering.

A calculation of the nuclear radius based, as before, on the energy at which the first decrease began leads to a value of 4.6 (10^{-13}) cm. This also is lower than the value calculated from Bethe's formula. Since the barrier height corresponding to this radius is 6.2 Mev, the assumed resonance energy is just below the top of the barrier. The excitation energy of the Mg^{24} nucleus at resonance is 14.7 Mev. This is higher than any resonance level previously found.

Conclusion

Data gathered on the scattering of alpha-particles by argon, oxygen and neon show the existence of anomalies in all three cases. Irregularities in the variation of the anomalies with energy in the cases of oxygen and neon are thought to be due to resonance levels of the associated compound nuclei. Calculations of radii of the scattering nuclei, based on the penetrability of the barriers, lead, in the cases of oxygen and neon, to values smaller than those calculated from Bethe's formula, but, in the case of argon, to a value higher than that given by the formula. This latter result agrees with the deductions of Pollard, Schultz, and Brubaker[3] from data on the disintegration of argon by alpha-particles.

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The Resonance Processes in the Disintegration of Boron by Protons

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The yields of long range alpha-particles and gamma-rays from the disintegration of boron by protons having energies from 150 to 195 kev were measured simultaneously. The shapes of the yield curves indicate that the yields for the two processes are proportional and that the resonances occur at the same voltage, to within 1 kev. A determination of the alpha-particle yield places the resonance point at 165 ± 4 kev. Thus it is highly probable that both resonance processes involve the same level in the excited C^{12} nucleus. The unsatisfactory findings of Oppenheimer and Serber are therefore probably not due to their assumption concerning the association of the resonances with the same energy level of the compound nucleus. The half-breadth of the alpha-resonance was estimated to be 6 kev, and could be accounted for by the spread in energy of the ion beam. Thus the estimates of Oppenheimer and Serber concerning the sharpness of the resonance processes are here supported.

Introduction

Various workers have reported conflicting data concerning the long range alpha-particle and gamma-ray resonances observed when boron is bombarded with protons. Williams, *et al.*,[1] observed a resonance of the long range alpha-particles at 180 kev. Bothe and Gentner[2] reported that gamma-rays were emitted which also indicated a resonance at 180 kev. Later Williams and associates,[3] using thin targets of boron, placed the alpha-particle resonance at 159 kev with a half-breadth of 10 kev. They also observed the gamma-ray resonance at about the same voltage. The spectrum of the gamma-rays was found to consist of three lines: 4.3 Mev, 11.8 Mev, 16.6 Mev with relative intensities of 1 : 1 : 1/7, respectively.[4]

These resonance processes are attributed to the following reactions:

$$B^{11}+H^{1}\rightarrow C^{12*}\rightarrow C^{12}+\gamma, \quad (1)$$

$$B^{11}+H^{1}\rightarrow C^{12*}\rightarrow Be^{8}+He^{4}. \quad (2)$$

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[1] Williams, Wells, Tate and Hill, Phys. Rev. **51**, 434 (1937).
[2] Bothe and Gentner, Zeits. f. Physik **104**, 685 (1937). Gentner, Zeits. f. Physik **107**, 354 (1937).
[3] Allen, Haxby and Williams, Phys. Rev. **53**, 325 (A) (1938).
[4] Fowler, Gaerttner, and Lauritsen, Phys. Rev. **53**, 628 (1938).