TABLE I. *Shower intensity as a function of magnetic latitude.*

Mag. Lat.	No. Counts	Min.	Rate	Barometer	Corr. Data
23°N	1282	1092	1.173	29.98	1.192
19	1783	1513	1.179	29.90	1.179
13	2020	1679	1.203	29.82	1.184
6	1601	1420	1.128	29.80	1.106
0	1678	1458	1.150	29.74	1.113
12°S	1667	1375	1.212	29.75	1.176
16	892	724	1.232	29.77	1.200
29	1011	907	1.113	29.88	1.108
34	1838	1534	1.198	29.94	1.208
38	1734	1576	1.101	30.03	1.130
41	4246	3436	1.234	29.89	1.232

ably on this correction because the barometer was low in the region of the magnetic equator. Because of the statistical fluctuations in the data these have been analyzed by dividing them into two groups with those readings taken at latitudes greater than 20° forming one group and those taken at latitudes smaller than 20° the other group. The averages of the corrected rates for these two groups are:

At latitudes greater than 20°

1.190 ± 0.012 counts/minute

At latitudes smaller than 20°

1.158 ± 0.011 counts/minute.

The mean errors have been computed from the total number of counts in the two cases.

The results seem to show a small latitude effect for these showers, but since the effect is only slightly larger than the statistical errors we do not feel that the experiments establish its existence with any certainty.

For the small showers emerging from a lead plate Neher and Pickering[2] report a latitude effect on the Pacific Ocean of about 6 percent.

If one considers the average area of the showers measured in this experiment as one square meter, and the particle density as 30 per square meter, as given by Auger, then the number of particles per shower is about 30. To produce such a shower at sea level by the cascade process, the primary energy would be of the order of 10^{12} ev. If, on the other hand, one considers that the energy loss per particle in penetrating the atmosphere is 3×10^{9} ev, the primary energy is still about 10^{11} volts. Hence, even for showers of this area, there should be no latitude effect.

We wish to express our grateful appreciation to the Carnegie Corporation of New York for making these experiments possible. We are also indebted to the Canadian-Australasian Line, and especially to the officers of the *S. S. Niagara* for the cooperation they rendered, even while under the stress imposed by the present international situation.

[2] H. V. Neher and W. H. Pickering, Phys. Rev. **53**, 111 (1938).

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The Scattering of Alpha-Particles by Carbon and Oxygen*

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The scattering of alpha-particles by carbon and oxygen has been observed at large scattering angles, with solid targets and RaC′ as a source. The results show resonances in carbon at energies of 5.5, 5.0 and 4.4 Mev and indicate that the angular momentum quantum number of the compound nucleus O^{16} is probably 2 for the highest level, and greater than zero for the others. Two resonances have been observed in oxygen at energies of 6.5 and 5.5 Mev. These indicate excited states of Ne^{20} whose angular momentum is probably unity. These two levels correspond very closely with those found by Bonner in the disintegration of fluorine by deuterons.

THE process of alpha-particle scattering by carbon and oxygen nuclei has some unusual features which make it relatively amenable to theoretical treatment and favorable for experimental investigation. These features arise from the fact that the spins of all nuclei concerned are zero and that at alpha-particle energies below 8 Mev the competing processes of proton

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or neutron emission are either excluded or extremely improbable because of the low available energy. The first fact makes it possible to reduce the expression for the ratio $\sigma(\theta)/\sigma_0$, of the actual to Coulomb scattering near an isolated level of the compound nucleus,[1] to the form

$$\frac{\sigma(\theta)}{\sigma_0}=\left|ae^{i\eta}+\frac{\rho e^{i\xi}}{x+i}\right|^2.$$

Here the Bethe formula has been modified to take account of a potential scattering background. $a\sigma_0^2$ is the cross section of this background, η is an unknown phase angle,

$$\rho=2(2J+1)\frac{\Gamma_{Pp}{}^r}{\alpha\Gamma_r}P_J(\theta)\sin^2(\theta/2),$$

$$e^{i\xi}=\frac{(1+i\alpha)\cdots(J+i\alpha)}{(1-i\alpha)\cdots(J-i\alpha)}\exp\left[i\alpha\log\sin^2(\theta/2)\right],$$

$$x=2(E-E_r)/\Gamma_r,\quad \alpha=2Ze^2/\hbar v.$$

Here J is the angular momentum of the compound state, E_r the corresponding alpha-particle energy, $\Gamma_{Pp}{}^r/\Gamma_r$ the ratio of the level width due to scattering to the total width, θ is the scattering angle in the center of gravity system and $P_J(\theta)$ is the Legendre polynomial of degree J.

The absence of competing processes now makes it possible to put $\Gamma_{Pp}{}^r/\Gamma_r=1$; if we assume inelastic scattering to be absent. This has the twofold advantage of determining ρ uniquely in terms of J and known quantities and ensuring that ρ has its maximum value. It also suggests that in these elements for energies at which there is considerable barrier penetration, there will be a relatively large potential scattering. We should, therefore, expect to find large scattering anomalies in these elements, especially at large angles where the potential scattering is greatest and where the angle variables in ρ have their maxima. It might, thus, be hoped that levels of the compound nucleus could be located by observation of the large angle scattering.

Although the relative feebleness of naturally radioactive sources with consequent lack of resolution in angle and energy makes them unsuitable for precise scattering analysis, a comparison of the results of earlier work with the theoretical predictions suggested that resonances might be located by their use. Observations by Riezler[2] at 90° on carbon and by Devons[3] at 90° and by Riezler[4] at 90° and by Brubaker[5] at 90–110° on oxygen indicated that there was a marked increase in the anomalies towards larger angles. Consequently the present experiments have been carried out at large angles, mainly 157°. Scattering from carbon was done at 157°, 137° and 112°, and from oxygen at 157°. The angular spread, in all cases, was about 15°. Solid targets were used; graphite for the carbon and lithium hydroxide for the oxygen.

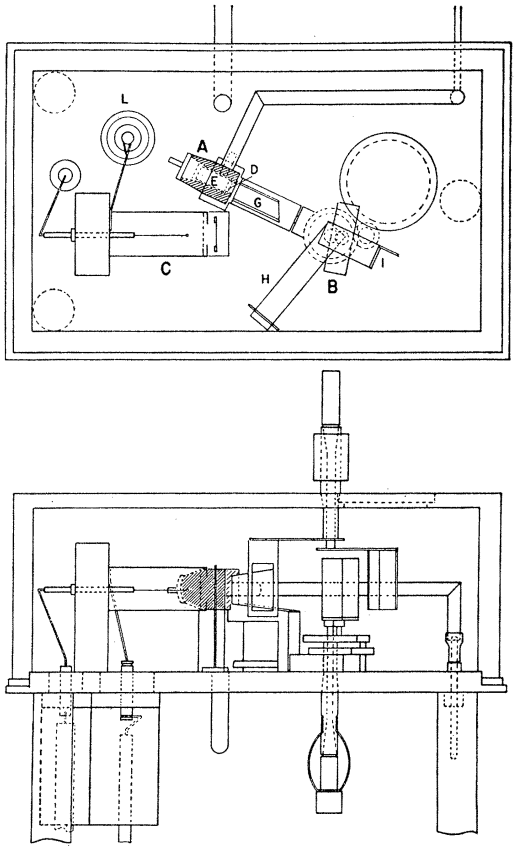

FIG. 1. Diagram of apparatus.

EXPERIMENTAL

The scattering chamber in which source, scatterer and detector were all placed, is shown

[1] H. A. Bethe, Rev. Mod. Phys. 9, §71 (1937).

[2] W. Riezler, Proc. Roy. Soc. **A134**, 154 (1932).
[3] S. Devons, Proc. Roy. Soc. **A172**, 127 (1939).
[4] W. Riezler, Ann. d. Physik **23**, 198 (1935).
[5] G. Brubaker, Phys. Rev. **54**, 1011 (1938).

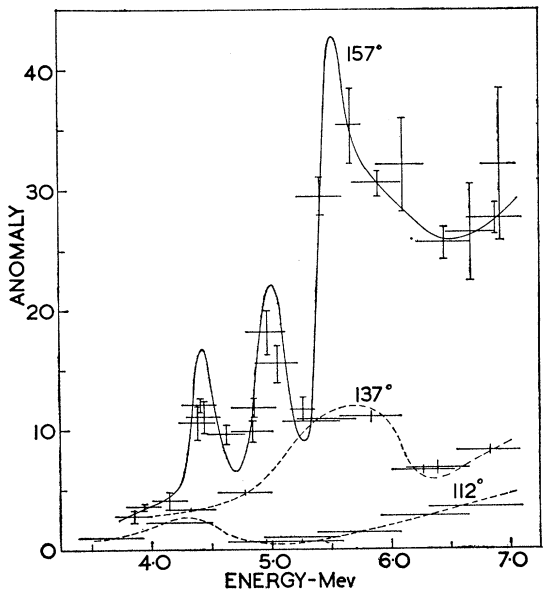

FIG. 2. Scattering from carbon.

in Fig. 1, and was formed by a brass base plate which carried several of the parts together with a brass lid resting on a rubber gasket around the base. The source, D, is a polished nickel button 5 mm in diameter on which RaC′ was deposited. Initial strengths ranged from 25 to 50 millicuries. The button is screwed into a cylindrical brass plug, E, and this is carried in a lead source chamber, A; the latter is closed in front by a permanent mica window of 7 mm air equivalent and behind by a tightly fitting plug, waxed into position. To avoid contamination by radon, it was essential to pump out the source chamber and the box in parallel, and to place a charcoal trap, cooled by a dry-ice acetone mixture, in the pump line of the former. The background count was, in this way, kept at from $\frac{1}{2}$ to $1\frac{1}{2}$ counts per minute. The incident beam is limited by the collimating tube, G, which is designed so as to avoid any scattering into the counter. By means of the shutters, H and I, operated from above, the source or counter may be closed off for background runs. The energy of the incident particles could be varied by interposing mica screens before the source chamber face.

Comparison of the actual scattering with classical scattering was effected by substituting in the position of the target of the light element a similar gold target. The target block, B, carried a thick layer of the light element on one side and a 2-mil gold sheet on the other; by means of external control, rotation through 180° could be effected. The target was mounted in such a way that, by means of a gear train, a rotation of the arm carrying the source left the target making equal angles with the incident and scattered beams. The possibility of using thick targets depends mainly upon that of obtaining a sufficiently flat surface. The effective thickness of the target is small because of the substantial energy loss involved in large angle scattering and, if necessary, it may be made smaller by placing an absorbing screen of known stopping power in front of the counter. However, flatness is essential for a calculation of the effective depth of penetration and, hence, of the number of scattering centers. Carbon targets were made by buffing strips of spectroscopic carbon with filter paper and also by buffing a surface formed of "Aquadag" with the protective colloid destroyed. Results with these surfaces were in satisfactory agreement. The oxygen targets were made by quickly fusing LiOH on an aluminum sheet so that Al_2O_3 was not destroyed; these surfaces were very smooth. Large angle scattering from H is impossible and negligible from Li due to the extremely low range after collisions with these light nuclei.

The close proximity of a very strong gamma-ray source to the detector makes an efficient counting system essential. By using a high gain linear amplifier, with a grid leak of 0.1 meg. in the first stage to minimize fluctuations in the gamma-ray current noise, and by working well below the breakdown voltage of a proportional counter, we were able to obtain a satisfactory working plateau in the count *vs.* voltage characteristic of the mixed alpha-particle and gamma-radiation. The proportional counters were of the wire type. To lower secondary production, the walls were made of 2-mil brass and the backs of paraffin, the paraffin serving as a support. The counters had no windows, and, together with the scattering box, were filled with hydrogen at 12 cm pressure. Hydrogen does not scatter alpha-particles into the counter and hydrogen nuclei cannot enter it at these angles. C is the counter assembly.

The procedure followed in taking observations was as follows: the source was closed off and a two-minute background count taken; the source was opened and a one-half or one-minute gold count made; the target was reversed and a ten-minute count made; the target was again reversed and a gold count made; then followed a background count, gold count, light element count, etc. The cycles were continued until the count from the light element fell to 4 per minute or the background rose to $1\frac{1}{2}$ per minute. In calculations, the decay of the source was taken to be linear over any individual count.

Analysis

The evaluation of the ratio from the experimental data involves certain special features when thick targets are used. The Rutherford scattering formula contains a term of the form N/E^2 where N is the number of scattering centers and E is the energy. For thick targets this becomes proportional to

$$\int_0^{x_0} \frac{dx}{s(R_0-x)E^2(R_0-x)},$$

where R_0 is the initial alpha-particle range, x the penetration into the target in cm air equivalent, $s(R_0-x)$, $E(R_0-x)$ the stopping power of the element and the energy for particles of range R_0-x, respectively, and x_0 the maximum depth of penetration, x_0 is found from the equation

$$\alpha E(R_0-x)=E(x_0+t)$$

where α is the fraction of energy retained by a scattered particle after collision and t the minimum range of a particle leaving the surface of the target which is just registered by the counter. This equation was solved by using Holloway and Livingston's data for air[6] in the cases of carbon and oxygen and Rosenblum's penetration-velocity measurements[7] for ThC′ particles in gold. The quantity t was set equal to the air equivalent of the hydrogen between the target and the counter face plus the air equivalent of screens in front of the counter, since experiments seemed to show that the residual range at the counter necessary for registration could be put equal to zero. The air equivalent of the hydrogen was found by replotting Mano's data[8] and some points from Gurney's work.[9]

A t in mg per cm^2 of gold corresponding to the energy of alpha-particles which have an air range t appears in the equation for x_0 for gold and its evaluation involves extrapolating Rosenblum's data. The accuracy of the extrapolation was checked by making measurements of the relative gold yields for different alpha-particle energies and comparing with calculated values based on a series of values for t.

For carbon and oxygen a knowledge of x_0 is sufficient to determine the yield integral, since for the small penetrations involved we may treat $s(R_0-x)$ as a constant and suppose the energy to be a linear function of the range. These assumptions are not possible for the gold integral where α is much larger and penetrations naturally deeper. It is possible to show that the integral here is proportional to

$$\int \frac{dw}{v^4}$$

taken between certain limits, where v=velocity, w=penetration in mg per cm^2 and $v=v(w)$ is the

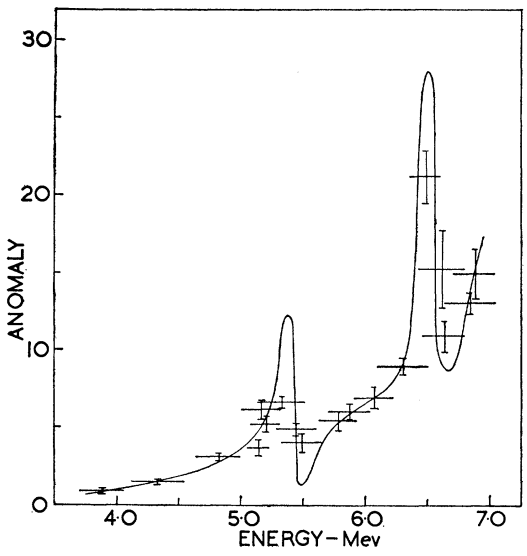

FIG. 3. Scattering from oxygen.

[6] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).
[7] S. Rosenblum, Ann. de physique **10**, 408 (1928).
[8] G. Mano, Ann. de physique **1**, 407 (1934).
[9] R. W. Gurney, Proc. Roy. Soc. **A107**, 340 (1925).

TABLE I. *Values of* $(\sigma/\sigma_0)_{\min}$ *for values of* J *and* α*-particle energies for carbon.*

E_r IN MEV	$J=0$	$J=1$	$J=2$	$J=3$
5.5	29.6	9.6	1.5	0.0
5.0	12.7	2.0	0.1	2.5
4.4	9.0	1.0	0.5	3.3

relation given by Rosenblum's data.

$$\int_0^w \frac{dw}{v^4}$$

was therefore integrated numerically from a plot of these data and the tabulated integral used to determine the gold yields. For the carbon and lithium hydroxide, the necessary stopping powers were obtained from Livingston and Bethe.[10]

RESULTS

The ratio of observed to Rutherford scattering is shown as a function of energy in Fig. 2 for carbon and Fig. 3 for oxygen. The carbon measurements were carried out at three different angles, 157°, 137° and 112°, while the oxygen measurements were made only at 157°. The height of the vertical line represents the statistical error in the counting of particles; the number of counts to a point varied in the light elements from 150 to 2500, a somewhat larger number being counted in all cases from the gold. The width of the horizontal line represents the energy range covered by a single observation, the limits being calculated for a homogeneous group of alpha-particles. Straggling causes some blurring of the edges of the energy distribution. It may be shown that, for the lower limit of the range, the straggling is less than that of alpha-particles whose energy has been reduced to the same mean value. The probable error has not been indicated in the carbon measurements at 112°, since it is small compared with the energy spread. The points at 137° are distinguished from the others by the omission of the horizontal bar at the ends of the vertical line indicating the error. The smooth curve has been drawn so that mean values over the actual experimental energy ranges agree fairly well with the observed values. Because of the relative coarseness of the energy resolution, the true height of the resonance peaks is somewhat uncertain. In oxygen, near the resonances, since these are far apart, the curve has been given the shape typical of an isolated level.

The results for the scattering in carbon appear to show evidence for resonance at alpha-particle energies of 5.5, 5.0 and 4.4 Mev. The estimated values of the anomalies at the resonance maxima are 43, 22 and 16.5, respectively. These resonances correspond, when the data of Barkas[11] are used, to excited states of O^{16} at 11.4, 11.1 and 10.6 Mev above the ground state with half-widths of 0.2–0.3 Mev. The barrier height for carbon is about 4.9 Mev, so that two of these levels lie above the barrier. The only other process leading to an excited state of O^{16} is the

$$_1H^1+{}_9F^{19}\rightarrow{}_2He^4+{}_8O^{16}$$

reaction, where, however, the levels involved lie much deeper.[12]

It is readily deduced from the single level formula that the anomalies at the maximum and minimum are given by

$$(\sigma/\sigma_0)_{\max}{}^{\frac{1}{2}}=(a^2+a\rho\sin\xi+\tfrac{1}{4}\rho^2)^{\frac{1}{2}}+\tfrac{1}{2}\rho,$$

$$(\sigma/\sigma_0)_{\min}{}^{\frac{1}{2}}=|(a^2+a\rho\sin\xi+\tfrac{1}{4}\rho^2)^{\frac{1}{2}}-\tfrac{1}{2}\rho|,$$

where $\xi=\zeta-\eta$. It follows that

$$\rho=(\sigma/\sigma_0)_{\max}{}^{\frac{1}{2}}\pm(\sigma/\sigma_0)_{\min}{}^{\frac{1}{2}}.$$

Precise knowledge of the maximum and minimum thus leads to two possible values for ρ. If the minimum for a resonance is not known, then it can only be inferred that ρ does not exceed $2(\sigma/\sigma_0)_{\max}{}^{\frac{1}{2}}$. The order in which the maximum and minimum occur is arbitrary and will depend on the sign of cos ξ which, in general, is not known. Using the calculated values of ρ and experimental values of $(\sigma/\sigma_0)_{\max}$ we obtain for the first four J values the values of $(\sigma/\sigma_0)_{\min}$ given in Table I.

Since ξ may vary across the energy intervals used and since there may be interference between different levels, a comparison of calculated and

[10] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, §95 (1937).

[11] W. H. Barkas, Phys. Rev. **55**, 691 (1939).

[12] W. B. McLean, R. A. Becker, W. A. Fowler, C. C. Lauritsen, Phys. Rev. **55**, 796 (1939); W. A. Fowler, C. C. Lauritsen, Phys. Rev. **56**, 840 (1939).

experimental heights cannot be held to have a great deal of significance. However, from the values given above, it seems likely that for the three levels observed, $J>0$. The highest level diminishes considerably in prominence at 137° (150° in the center of gravity system) and disappears completely at 112° (130°), suggesting very strongly that here $J=2$, since $P_2(125°)=0$.

Devons[3] in his work on the scattering of alpha-particles from carbon at 90° finds only one resonance corresponding to a broad peak at 5.8 Mev. However, it is noticeable that there are small peaks present in his experimental data at energies close to the resonance values found here. In assigning the value $J=1$ to the level which he finds, Devons makes use of an incorrect formula for the resonance scattering.

Inasmuch as the height of the 5.5-Mev resonance found by us was considerably greater than that found by Riezler in a comparable range, a check was made on the experimental procedure and analysis of results. For this purpose, a few runs were made with a copper scatterer and the ratio of observed to Coulomb scattering found to be within 10 percent of unity, which is less than the errors due to ignorance of the full range-energy relation of copper. Some runs with aluminum and boron also gave results comparable with Riezler's. The possibility of contamination of the graphite was ruled out by failure to observe scattered particles of long range, and by the departure of the results from the angular dependence expected with such an impurity.

The data for oxygen show two distinct resonances at 6.5 and 5.5 Mev. A J value of zero is definitely too small to enable the curve to pass through the points at either resonance without assuming that the background scattering changes suddenly in this neighborhood. The values for ρ obtained from the curve, and the formula quoted above, are 2.37 for the upper and 2.36 for the lower, if the negative sign is taken. These correspond fairly well to those for $J=1$ in both cases. If the positive sign is taken, the values obtained are 8.23 and 4.64, respectively. The value for the upper resonance is out of the question, and, for the lower, would indicate that J was 3 or 4, which is improbable. It thus seems that we can reasonably set $J=1$ for both levels. In Table II, ρ is given for values of J up to 4.

TABLE II. *Values of ρ for oxygen.*

E_r IN MEV	$J=0$	$J=1$	$J=2$	$J=3$	$J=4$
6.5	0.99	2.83	4.30	5.20	5.38
5.5	0.89	2.55	3.87	4.68	4.85

The resonances do not appear clearly in the work of either Devons or Brubaker. This, however, lends support to the idea that they are P levels, since the work of these investigators was carried out in the neighborhood of 90°, where they would be small due to the proximity of the zero in $P_1(\theta)$.

The two resonances arise from excited states of Ne^{20} at 10.1 and 9.0 Mev above the ground state. These are in exact agreement with those found by Bonner[13] in the reaction

$$_1H^2+{}_9F^{19}\rightarrow{}_{10}Ne^{20}+{}_0n^1.$$

It would thus appear that alpha-particle groups corresponding to the two excited states should appear in the bombardment of fluorine by deuterons. This has been done by Burcham and Smith[14] whose measurements, unfortunately, do not go to a low enough range, i.e., below 3 cm, to detect particles from the upper level. According to Bonner, these investigators actually found a group at 2.8-cm range, which would correspond to this level, but they apparently deleted it from their data due to the possibility of its arising from carbon contamination.

ACKNOWLEDGMENTS

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[13] T. W. Bonner, Proc. Roy. Soc. **A174**, 339 (1940)
[14] W. E. Burcham and C. L. Smith, Proc. Roy. Soc. **A168** 176 (1938).