An examination of the statistics of the problem shows that if in an appreciable fraction of ionic spurts, say 20 percent as observed, the counters also record, then the number of rays is probably not considerably less than what would correspond to an average of one ray through each counter set. Taking into account the average distances involved, we are led to the conclusion that the nuclear disintegrations observed corresponded to at least 100 secondaries, and may of course represent many more. The possibility of there being more secondaries than would correspond to the total number of electrons and protons in the disintegrated atom naturally raises interesting considerations regarding the mechanism of the processes accompanying the disintegration.

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Scattering of Molecular Rays in Gases

Knauer[1] has recently investigated the scattering of molecular rays in gases. By the aid of high speed pumps the author has found it possible to produce a more intense beam so that scattering might be investigated with higher resolving power.

A beam is formed by three successive slits and the distribution of the scattered molecules or atoms studied by the aid of a Pirani gauge. Two slits placed before the gauge permit molecules to enter it only when they are scattered from a definite position in the beam.

Fig. 1 (curves *A* and *B*) shows the scattering curves which have been obtained for hydrogen molecules and helium atoms. The temperature of the source of the beam and scattering chamber was 20°C. The scattered intensity is expressed in arbitrary units, being simply the galvanometer deflection multiplied by sin θ to correct for the variation in the length of the beam from which scattered molecules may enter the gauge.

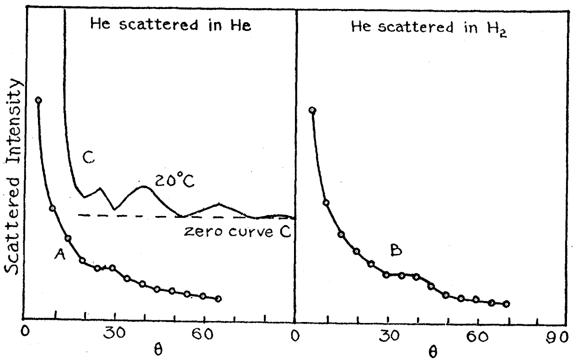

Fig. 1. Curve *A*, He scattered in He; curve *B*, H_2 scattered in H_2; curve *C*, results of Massey and Mohr for He scattered in He.

Massey and Mohr[2] have computed the scattered intensity for helium atoms having a relative kinetic energy corresponding to 20°C and -185°C. The results which they have obtained offer a qualitative explanation of the helium scattering curve. Curve *C* (Fig. 1) is reproduced from their article after being multiplied by sin 2θ and divided by sin θ to obtain the scattering per unit solid angle in a coordinate system in which one atom is initially at rest. One peak occurs at 25° and another at 40°. From a qualitative point of view three effects are immediately obvious which would tend to merge these two peaks into the one observed at 30°. The first is the finite resolving power of the apparatus, second the Maxwellian distribution of velocities in the beam and third the fact that the scattering molecules are not at rest but are moving in random directions with a Maxwellian distribution of velocities.

The intensity of the region of 65° is too small to determine definitely whether a peak exists there.

A complete report will appear in a short time.

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June 3, 1933.

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[1] Knauer, Zeits. f. Physik **80**, 80 (1933).

[2] Massey and Mohr, Nature **130**, 277 (1932).

On the Production of the Positive Electron

The experimental discovery of the positive electron gives us a striking confirmation of Dirac's theory of the electron, and of his most recent attempts to give a consistent interpretation of the formalism of that theory. As is well known, and quite apart from the difficulties connected with the existence and stability of the electron itself, the theory in its original form led to very grave difficulties in all problems involving lengths of the order of the Compton wavelength, in that it predicted the occurrence of electrons of negative kinetic energy, in gross conflict with experience. Dirac has pointed out that we might obtain a consistent theory by assuming that it is only the absence of electrons of negative kinetic energy that has a physical meaning; in this way one could avoid the occurrence of the critical transitions, and yet understand the validity of many correct predictions of the theory, such as the formula for the relativistic fine structure, and the Thomson and Klein-Nishina scattering formulae: only the physical interpretation of the formulism was changed, and involved in many cases the appearance pairs of electrons and "antielectrons"

—particles of electronic mass and of positive charge numerically equal to that of the electron. It was this aspect of the theory which remained dubious; and the discovery of the positive electron appears to settle that doubt.

Perhaps the simplest example of the production of pairs is the case of an externally maintained electrostatic field in which differences of potential greater than 2 mc^2 occur. Here one may see in a particularly clear way that the production of pairs is a typical quantum effect, depending upon the finite wave-length of the electron waves, and disappearing, as the correspondence principle requires, when $h\rightarrow 0$. For all macroscopic fields such an effect is negligible; and for the fields within nuclei, where alone the pairs might be expected to be of primary importance, we know that Dirac's theory, together with the whole notion of the electron as a particle, becomes inapplicable. It is for this reason that the anti-electrons could so long escape detection.

In the case of a Coulomb field the theory shows that to detect the pairs we should have to use radiation (electrons or gamma-rays) of energy greater than 2 mc^2 (strictly greater than $mc^2[1+(1+\alpha^2Z^2/(1-\alpha^2Z^2)^{\frac{1}{2}})^{-\frac{1}{2}}]$ where Ze is the charge producing the field). Thus, if we allow gamma-rays of energy γ to fall upon a nucleus, we should expect pairs to appear; the kinetic energy of the pairs would be $\gamma-2$ mc^2; and the effect might be interpreted as a photoelectric absorption of the gamma-ray by the pair; in the process the nucleus necessarily takes up a small recoil momentum. The recent experiments of Anderson and Neddermeyer with filtered gamma-rays of Th C″ show that in fact pairs are produced when the radiation passes through lead; and this very strongly supports the tentative suggestion made by Blackett and Occhialini that that part of the absorption of these rays in lead which cannot be accounted for by the scattering and photo-effect of the atomic electrons is to be ascribed to the creation of pairs near the nucleus. This hypothesis, even without calculation, finds much support in the evidence, for the number of pairs observed by Anderson and Neddermeyer is of the right order to account for the excess absorption of the gamma-rays. Further Gray and Tarrant[1] have found that a part, but not all, of the excess energy absorbed is reradiated; the reradiated gamma-rays consist, wholly for the light elements, and for the greater part in lead, of quanta of energy 5×10^5 volts. This is what we should expect from the pairs, which should lose practically all of their kinetic energy in passing through matter, and in which the anti-electron near the end of its range should combine with an electron with the radiation of two quanta of about a half-million volts.

We have applied the theory to this simple model, in which gamma-rays of high energy may be absorbed by the production of pairs in the Coulomb field of nuclei. When the energy of the gamma-rays is only a little greater than the threshold energy, and the kinetic energy of the pair is small, so that relativistic effects for electron and positive may reasonably be neglected, the calculations can easily be made strictly. The important term in the effective absorption cross section per nucleus (of charge Z) for gamma-rays of energy γ is

$$\sigma=(\pi/3\ (2)^{\frac{1}{2}})\alpha^4Z^5(e^4/m^2c^4)g^{\frac{3}{2}}e^{-2\pi\alpha Z(2g)^{-\frac{1}{2}}};\quad \text{with}\quad g=\gamma/mc^2-2. \qquad (1)$$

The positives tend to take most of the available kinetic energy, and the distribution in the direction of ejection of the particles about the direction of the incident gamma-rays is given by the cosine-square law.

For higher energies of the gamma-rays, we have made an approximate calculation, in which we have found the wave functions for the pair to the first order only in the perturbing field of the nucleus. For $\gamma\rightarrow\infty$ we find asymptotically

$$\sigma=(\pi^2/6-2/3)\alpha Z^2e^4/m^2c^4. \qquad (2)$$

Here the relative probability of a distribution of energy between positive (ϵ_+) and electron (ϵ_-) is given by

$$\epsilon_+^2+\epsilon_-^2 \qquad (\epsilon_+\gg mc^2;\quad \epsilon_-\gg mc^2). \qquad (3)$$

Both particles tend to come off within a small angle of the original beam. The probability of ejection falls off rapidly for angles $\gg mc^2/\epsilon_+$, mc^2/ϵ_- for the two particles.

From (2) we see that the excess absorption of hard radiation should be proportional to Z^2, in good agreement with the experiments with Th C″ gamma-rays. Further, even the asymptotic formula (2) gives reasonable values for the absolute magnitude of the excess absorption. Numerical calculation for the case of Th C″, $\gamma\cong 2.6\times 10^6$ v (with the use of the same approximate wave functions), gives an excess absorption of about 25 percent of the Klein-Nishina absorption of these rays in lead, and 15 percent in tin, in excellent agreement with experiment. We see too from a comparison of (1) and (2) that the absorption due to the production of pairs rises very rapidly as the energy of the gamma-rays is increased; at half the energy of the Th C″ rays the absorption is only one five-hundredth as great. The small effect for gamma-rays near the threshold arises in part from the small number of states available, and in part from the repulsion of the low energy positive by the nuclear field. In this way we can understand that the excess absorption and the reradiated gamma-rays were not observed with incident gamma-rays of energy much lower than 2×10^6 volts. Thus the theory gives a reasonable account of the dependence of the excess absorption on the gamma-ray energy and on the atomic number and of the absolute magnitude of the absorption. The origin of the radiation of $\sim 10^6$ volts which Gray and Tarrant found reradiated from heavy element is not altogether clear. It is possible that this arises by the annihilation of a positive in a process in which only one quantum is radiated, and an electron or nucleus takes up a small recoil momentum. The relative importance of such processes would increase with the atomic number, as is observed.

According to the theory the gamma-rays from a radioactive nucleus should occasionally be "internally converted" by the production of a pair near the nucleus. The internal conversion coefficient is of the order α^3Z^2, and is

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[1] Gray and Tarrant, Proc. Roy. Soc. **A136**, 662 (1932).

about 2×10^{-4} for the quadripole gamma-ray of Th C″, $\gamma\leqq 2.6\times10^6$ volts.

The application of (2) to the absorption of cosmic rays is in some respects illuminating. For as the energy of the gamma-ray is increased, the absorption by the production of pairs becomes relatively more important than the absorption by Compton effect. This would account for Anderson's observation that among high energy particles the numbers of positives and negatives are roughly equal; and it would increase the energy of the gamma-rays as estimated from their absorption coefficients. Further (2) gives a limiting penetration, which is of the same order for water as that observed for the hardest cosmic rays. Nevertheless (3) is here in definite disagreement with experiment, in that a penetration in water twice as great as that predicted by (2) has been observed by Regener, and further in that (2) predicts serious deviations from the mass absorption law which are certainly not found experimentally. It appears that deviations from the Coulomb law for the nuclear fields could not sensibly affect our result; and one is tempted to see in this discrepancy a failure of the theory when applied to radiation whose wave-length is of the order of the critical distance e^2/mc^2 which marks the limit of applicability of classical electron theory. But we must emphasize that (2) was derived by the use of approximations which may be unsound; just in the range of high energies and large atomic numbers their validity appears doubtful; and we believe that no conclusions may justly be drawn until this purely analytical point is settled. Even for light elements the use of (2) for γ greater than 10^8 volts appears to us questionable.

On the present simple theory there is no place for the simultaneous production of large numbers of pairs. The fast electrons and positives, however, will themselves tend to produce further pairs; and although this point too wants much closer investigation, it is possible that one may so be able to account for the multiple tracks observed.

We want to express our profound thanks to Professor Bohr, who has helped us to understand the essential consistency of the theory which we have here applied.

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June 9, 1933.

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The Emission of Alpha-Particles from Various Targets Bombarded by Deutons of High Speed

Using a sample of hydrogen containing 50 percent of the heavy isotope, H^2, in our apparatus for the multiple acceleration of ions we have given to the ions H^1H^{2+} energies of 2,000,000 volts. These ions striking any target immediately yield 660,000 volt-protons and 1,330,000 volt H^2 nuclei which we call deutons. We have directed these particles against various targets.

It was of particular interest to study elements of the nuclear type $4n+2$ in order to ascertain whether these would yield nuclei of type $4n$ and α-particles. As a matter of fact the two targets which were most striking because of the range and number of emitted α-particles were NH_4NO_3 and LiF, which contained the nuclei N^{14} and Li^6. Experience with other targets containing O, H and F shows that most of the effects observed were due to N and Li. N yielded about 100 α-particles per 10^9 deutons all apparently homogeneous with a range of 6.8 cm. The minimum deuton energy at which we observed this disintegration was 600,000 volts. The energy of the α-particles obtained in this disintegration is only about one-half of that which should be set free in the process $N^{14}+H^2\rightarrow C^{12}+He^4$.

With Li a large number of α-particles of range 8.2 cm were obtained which are very likely due to the accompanying protons. In addition there are about one-tenth as many with the great range of 14.5 cm corresponding to an energy of 12,500,000 volts. No other known natural or artificial disintegration has yielded particles of so great energy. If we assume the process $Li^6+H^2\rightarrow 2He^4$ and take for He the mass 4.0022 and for H^2 and Li^6 the most recent values of Bainbridge, which he has kindly communicated to us, the values 2.0136 and 6.0145, respectively, and take account of the kinetic energy of the deuton (1,300,000 volts), we find 23,400,000 volts as the total energy set free. If this energy is equally divided between the two α-particles, each would have 11,700,000 volts, whereas, from the observed range we find 12,500,000 volts. This calculation of the energy from the range is a wide extrapolation, with the use of the 3/2 power voltage range relation, and the agreement between the observed and calculated values is well within the limits of uncertainty because of this and other causes. An alternative, but less likely hypothesis, that the process involves Li^7 with the emission of a neutron, happens to agree equally well with the observations if the mass of the neutron has the low value (about unity) that we discuss later.

With the Be target α-particles were obtained of the same range (3.3 cm) as those obtained in this laboratory in similar experiments with high speed protons. But the number of disintegrations per deuton was at least 100 times as great as the number per proton. The identity of the two ranges strongly suggests that the bombarding particle merely causes the disintegration of the unstable Be nucleus; in other words, that we have disintegration without capture. This is a process which has already been suggested by Bainbridge[1] for the disintegration of Be by α-particles. If we take Bainbridge's value for the mass of Be, 9.0155, our value for the kinetic energy of the α-particles and Chadwick's[2] for the kinetic energy of the neutron, the mass of the neutron would come out as a little less than unity, which tends to confirm the estimate of the mass of the neutron (following communication) which we have obtained from quite different experiments.

Of the remaining targets studied, Al and Mg gave a small

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[1] Bainbridge, Phys. Rev. **43**, 367 (1933).

[2] Chadwick, Proc. Roy. Soc. **A136**, 692 (1932).