THE CONSERVATION OF ENERGY AND MOMENTUM
IN ELEMENTARY PROCESSES

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§ 1. INTRODUCTION

The mechanical principles of the conservation of energy and momentum are immediate consequences of Newton's laws of motion and therefore lie at the base of all classical mechanics. Their domain has been extended, by postulating additional forms of energy, such as that of the electro-magnetic field, and they have been taken over into the quantum mechanics without any essential modification. These laws were deduced from observations on macroscopic bodies and their extension to atomic dimensions requires independent confirmation.

It is convenient to distinguish two possible ways in which the conservation laws might break down.

Firstly some process may always involve the disappearance (or appearance) of energy or momentum, unaccompanied by any observable change in the rest of the universe. Such a "one-way" non-conservation could in principle be detected by macroscopic experiments, and the methods for the detection of single particles would only be used in this case because of their convenience. We shall discuss this type of non-conservation in connexion with the β-ray disintegration. We may point out that it is generally possible to rescue the conservation laws in cases of this type by postulating new forms of energy.

Secondly the conservation laws may hold if the average of a large number of individual processes is taken, but the individual processes themselves may not obey the conservation laws. This statistical interpretation was proposed by Bohr, Kramers, and Slater for all processes involving radiation. Their theory has been experimentally tested for the Compton effect, and we shall discuss the results obtained under that heading. In order to detect this type of non-conservation it is necessary to observe each of the particles taking part in one individual process. This can only be done in rather special cases, when the particles are charged and have a high velocity.

In the following we shall discuss a number of processes from this point of view. For the most part we shall deal with the interaction of high energy particles, because with these new types of phenomena, involving non-conservation, might be expected to occur. We have classified the experimental evidence according to the type of particles taking part. Thus §2 is devoted to the mutual interaction of heavy particles (atomic nuclei, neutrons etc.). Phenomena connected with the emission of light particles (electrons, positrons) are discussed in §3 while the interaction of radiation and matter is dealt with in §4. In each case a general familiarity with the phenomena is assumed so that attention may be confined to the relevant experimental evidence.
§ 2. COLLISIONS BETWEEN ATOMIC NUCLEI

Elastic collisions; cloud-chamber work. The investigations of Blackett and his collaborators\(^{(1)}\) on the forked tracks due to collisions between \(\alpha\)-particles and other nuclei in the cloud chamber are well known. Their work is summarized in *Radiations from Radioactive Substances*\(^{(2)}\) and more recently Blackett and Lees\(^{(3)}\) have given a careful discussion of the accuracy of these measurements. Some measurements have also been made by Wells and White\(^{(3)}\) on the collisions of fast protons passing through hydrogen.

It is found in these experiments that the conservation laws apply to the majority of collisions within the experimental error, but there are a few cases of apparent non-conservation. Amongst these the forks corresponding to disintegrations can generally be distinguished by the different appearance of the track of the ejected proton from that of the incident \(\alpha\)-particle. There remain *some* forks in which there is no sign of disintegration, but nevertheless the conservation laws are violated, for instance the three branches of the fork may not lie in one plane. [This might be due to the ejection of a neutron without capture of the \(\alpha\)-particle, except that such a process involves a large absorption of energy (\(10\) MV.*).] These anomalous forks are generally ascribed to experimental accidents such as the scattering of one of the particles by an atom of the gas, close to the point of collision. However, until recently this explanation had not been established experimentally.

Occasional examples of apparent non-conservation are also observed when photographs are taken of the emission of \(\alpha\)-particles by radioactive bodies, such as actinon, in the cloud chamber. If a sufficiently low gas pressure is used, the track of the recoiling \(\text{Ac-A}\) nucleus can be seen. It should of course lie in the same line as the track of the \(\alpha\)-particle. Such photographs have been taken by Akiyama\(^{(4)}\). He found that the track of the recoiling \(\text{Ac-A}\) nucleus frequently made angles up to \(15^\circ\) with the track of the \(\alpha\)-particle. It was difficult to explain this by a subsequent collision between the \(\text{Ac-A}\) and an atom of the gas, because in such a collision the deflection of the heavy \(\text{Ac-A}\) nucleus could not exceed \(4^\circ\). Akiyama made the unlikely suggestion that some very hard radiation was emitted at the moment of disintegration.

This phenomenon was investigated in greater detail by Joliot\(^{(5)}\). By using still lower pressures of gas (\(\sim 1\) cm. of mercury) he was able to distinguish a third track whenever the \(\text{Ac-A}\) recoil was not in the expected direction. This shows quite clearly that the apparently anomalous disintegrations are due to the deflection of the recoiling \(\text{Ac-A}\) nucleus by a collision between it and one of the atoms of the gas. The probability of such a collision was found to be very high. It is reasonable to extend the same explanation to the anomalous forked \(\alpha\)-particle tracks.

The fact that the heavy recoil nucleus can be deflected through large angles by collisions with the comparatively light gas atoms has still to be explained. Joliot investigated these collisions, and found many examples of scattering through larger angles than would be expected. He suggests various explanations, none of which is satisfactory. The present position is that anomalous recoil tracks, and therefore

\* Throughout this report MV. will stand for million electron volts.
probably the anomalous forks, are accounted for by scattering, but the details of the process are still in doubt.

**Disintegrations. The test of Einstein's equation.** In discussing the great wealth of experimental work on nuclear disintegration it is only possible to touch on a few problems which are of special interest. Any disintegration may be used to test the conservation of energy as expressed in Einstein's law of equivalence of mass and energy \( E=mc^2 \). For this purpose the masses of the nuclei must be known accurately, by means of mass spectrograph work; and the energy released in the disintegration must be known.

We may take as an example the disintegration

\[ ^{14}\text{N} + ^2\text{D} \rightarrow ^{12}\text{C} + ^4\text{He}. \]

This has been observed by Lawrence, McMillan and Henderson\(^5\), and by Cockcroft and Lewis\(^7\). The experimental value of the energy release is \( 13.22 \pm 0.1 \) MV. This is obtained from the range of the \( \alpha \)-particles in mica, making allowance for the energy carried away by the recoiling \( ^{12}\text{C} \) nucleus.\(^\dagger\)

This might be compared with the difference between the masses on the two sides of equation by substituting the masses given by Aston\(^8\). However the errors in these masses are not independent. The primary measurements from which the masses are deduced are the doublet separations, e.g. the difference between the values of \( m/e \) for the ions \( ^1\text{H}_2^+ \) and \( ^2\text{D}_1^+ \). To obtain a reliable estimate of the accuracy the energy changes in disintegrations must be calculated directly from these measurements. This method has been used by Bainbridge in discussing several disintegrations.

We give here the doublet separations obtained by Aston and Bainbridge separately, as there is some discrepancy between them.

We have

\[
\begin{align*}
^{14}\text{N} \rightarrow ^{12}\text{C} \quad & ^1\text{H}_2 = -0.01245 \pm 0.00007 \quad \text{Aston} \quad -0.0130 \pm 0.0002 \quad \text{Bainbridge and Jordan}^9 \\
^1\text{H}_2 \rightarrow ^2\text{D} = 0.00152 \pm 0.00004 & \quad 0.00153 \pm 0.00004 \\
^2\text{D}_1 \rightarrow ^4\text{He} = 0.02551 \pm 0.00008 & \quad 0.02572 \pm 0.00009
\end{align*}
\]

By addition

\[
( ^{14}\text{N} + ^2\text{D} ) - ( ^{12}\text{C} + ^4\text{He} ) = 0.01458 \pm 0.00011 \quad 0.01404 \pm 0.00022
\]

The above are in terms of \( ^{16}\text{O} = 16\cdot0000 \). Converting to units of energy, by using Einstein's equation, we obtain

\[
\begin{align*}
\text{Aston} & \quad 13.6 \pm 0.15 \text{ MV.} \\
\text{Bainbridge} & \quad 13.1 \pm 0.2 \text{ MV.} \\
\text{Experiment} & \quad 13.22 \pm 0.1 \text{ MV.}
\end{align*}
\]

The agreement is probably as good as can be expected at the present stage. The Einstein law is verified within about \( \pm 0.3/13 = 2 \) per cent.

\* We shall regard Einstein's law as an accurate expression of the conservation law, and interpret any deviation from it as due to non-conservation. We shall see that within the experimental accuracy conservation holds, and so the question of whether an alternative formulation of Einstein's law would be justified does not arise.

\^ In correcting for the energy of recoil, conservation of momentum has to be assumed.
The same type of calculation can be carried through for the reaction

\[ ^6\text{Li} + ^2\text{D} \rightarrow ^2\text{He}. \]

Bainbridge,*(16) has measured the doublet separation \(^6\text{Li} - ^2\text{D} ,\) assuming a deuteron mass of 2.01363, he obtained 0.0145 for Li. Hence his doublet separation, was 0.0264 with an error \(\pm 0.0003.\)

\[ \therefore \quad ^6\text{Li} + ^2\text{D} - ^4\text{D} = -0.0264 \pm 0.0003 \]
\[ ^4\text{D} - ^2\text{He} = 0.0510 \pm 0.00016 \quad \text{(Aston)} \]
\[ \therefore \quad ^6\text{Li} + ^2\text{D} - ^2\text{He} = 0.0246 \pm 0.0003 \]

which
\[ = 22.88 \pm 0.3 \text{ MV.} \]

The experimental value \(^{12}\) of the energy release is 22.06 \(\pm\) 0.07 MV. The difference 0.8 \(\pm\) 0.3 is not significant. Again the Einstein law is verified with an accuracy of 4 per cent.

These two reactions provide perhaps the best verification of the Einstein law because of the large energy releases involved. Many examples of smaller energy releases could be given, for instance

\[ ^{19}\text{F} + ^1\text{H} \rightarrow ^{18}\text{O} + ^4\text{He}, \]

for which Aston's figures give 8.1 \(\pm\) 0.3 MV., and experiment\(^{(11)}\) 8.25 \(\pm\) 0.2, and finally an example discussed by Jordan and Bainbridge\(^{(12)}\)

\[ ^{14}\text{N} + ^3\text{D} \rightarrow ^{15}\text{N} + ^1\text{H}, \]

for which the mass data give 8.57 MV. \(\pm\) 0.2 and experiment\(^{(7)}\) 8.53 \(\pm\) 0.1 MV.

The accuracy in the mass spectrograph measurements is lower than that attainable in the measurement of disintegration energies. It is possible to devise tests of the conservation laws involving only disintegration data, and these have a higher accuracy. The following three disintegrations have been investigated very thoroughly, and established by experiments with Wilson cloud chambers, and with separated isotopes.

\[ ^7\text{Li} + ^1\text{H} \rightarrow ^2\text{He} + ^1\text{H} + 17.06 \pm 0.06 \text{ MV.} \quad \ldots \quad (1), \]
\[ ^6\text{Li} + ^2\text{D} \rightarrow ^2\text{He} + 22.06 \pm 0.07 \text{ MV.} \quad \ldots \quad (2), \]
\[ ^6\text{Li} + ^2\text{D} \rightarrow ^7\text{Li} + ^1\text{H} + 5.0 \pm 0.05 \text{ MV.} \quad \ldots \quad (3). \]

The values for the energy releases are those given by Oliphant, Kempton, and Rutherford\(^{(13)}\). Subtraction of equation (3) from (2) gives (1). It will be seen that the energy checks within an uncertainty of 100,000 eV. Expressed as a fraction of the total energy release involved, 44 MV., this is 0.2 per cent. However this agreement would still exist if the \textit{same proportion} of the energy of disintegration were lost in each disintegration by such processes as radiation, interaction with neutrinos, outer electrons, or simple non-conservation. It is, of course, unlikely that these processes would take place to exactly the same extent in three different disintegrations, but this point must be remembered in assessing the accuracy of this check on the conservation laws.

* This determination is rather old, and was made by less reliable methods than the others quoted here. This particular example should therefore be treated with reserve.
The conservation of energy and momentum in elementary processes

Until recently the heavy, natural, radioactive elements could not be used for a test of Einstein's equation. The difference between the accepted atomic weights of uranium and radium for instance could be compared with the total mass and energy emitted in the radioactive series between these two elements, and similarly for radium \( \rightarrow \) Ra G and thorium \( \rightarrow \) thorium D.

If this was done discrepancies of the order of 0.2 in the atomic weights or \( 2 \times 10^8 \) eV. were found. These were almost certainly due to the inaccuracy of the chemical atomic weight determinations.

Very recently Dempster\(^{14}\) has made the first accurate determinations of the masses of uranium and thorium, and has followed this by a determination of the masses of the end products of these two series Ra G and Th D. These new masses now agree with the conservation laws, within the rather large limits of error. For instance the total emission of energy in the uranium series is 52 MV. and the mass change gives \( 57 \pm 10 \) MV.

*The conservation of momentum.* So far we have not considered the evidence on the conservation of momentum,\(^{*}\) nor the question of whether the energy of disintegration is strictly constant or has only a statistical meaning.

We may first consider the evidence on this point obtained in experiments with a cloud chamber. The older work is mainly concerned with the disintegration of nitrogen by \( \alpha \)-particles according to the equation

\[
^{14}\text{N} + ^{4}\text{He} \rightarrow ^{17}\text{O} + ^{1}\text{H}.
\]

Blackett and Lees\(^ {12}\) have collected and discussed the data on the eight forks which are most suitable for exact measurement. With the exception of one anomalous fork (of which the explanation is probably that offered above for the anomalous elastic collisions) these showed a mean energy change (\( -1.3 \) MV.) nearly the same as that found in experiments using electrical counting. The mean deviation from this value (\( 0.4 \) MV.) was that to be expected from the experimental errors. The forks also showed by their coplanarity that momentum was conserved.

Later work using the cloud chamber on other disintegrations has confirmed these conclusions. Thus, using artificially accelerated ions, Dee and Walton\(^ {15}\) showed that the two \( \alpha \)-particles from the disintegration

\[
^{7}\text{Li} + ^{1}\text{H} \rightarrow ^{4}\text{He}
\]

were emitted in opposite directions with equal momenta, and Dee\(^ {16}\) showed that the same applies in the disintegration

\[
^{2}\text{D} + ^{2}\text{He} \rightarrow ^{3}\text{H} + ^{1}\text{H}.
\]

Another instance of the same type is the disintegration of boron and lithium by slow neutrons

\[
^{6}\text{Li} + ^{1}\text{n} \rightarrow ^{4}\text{He} + ^{3}\text{H},
\]

\[
^{10}\text{B} + ^{1}\text{n} \rightarrow ^{7}\text{Li} + ^{4}\text{He}.
\]

* Since energy and momentum form one four-vector in relativity theory, the conservation of energy in any process might be regarded as a sufficient guarantee that momentum is also conserved. The conservation of energy is moreover a much more sensitive test of losses by radiation or neutrinos. However for the sake of completeness we consider separately the direct evidence on the conservation of momentum.*
Traces caused by these disintegrations in a photographic emulsion show that the two particles are ejected in opposite directions\(^{(17)}\). Since the neutrons causing the disintegration are slow there is no allowance to be made for the initial momentum.

In disintegrations by neutrons, Kurie\(^{(18)}\) has suggested that the straightforward application of the conservation laws as above may be no longer valid. He investigated the reaction

\[ ^{14}\text{N} + n \rightarrow ^{11}\text{B} + ^{4}\text{He}, \]

and found a constant value, not for the difference between the kinetic energies of the particles on the two sides of the equation, but for the sum of the kinetic energies of the \(^{11}\text{B} + ^{4}\text{He}\) alone.\(^*\) He suggested that the neutron was first captured to form a radioactive \(^{15}\text{N}\), emitting its surplus energy as \(\gamma\)-radiation, and that the \(^{15}\text{N}\) then split up into \(^{11}\text{B}\) and \(^{4}\text{He}\) with a definite "proper disintegration energy". This theory was discussed in the last report. Since then Bonner and Brubaker\(^{(19)}\) have also obtained evidence of this kind.\(†\) There are strong theoretical objections to this novel type of disintegration, and particularly in view of the large errors which can occur in measuring the neutron energy it should be regarded with reserve.

*Is the energy of disintegration constant?* Other evidence on the conservation of energy in the individual disintegrations can be drawn from the homogeneity of the groups in absorption curves taken with counters. For instance in the disintegration

\[ ^{7}\text{Li} + ^{1}\text{H} \rightarrow ^{2}\text{He}, \]

Oliphant, Kempton and Rutherford\(^{(13)}\) compared the \(\alpha\)-particle group with that from a radioactive source. The disintegration group was found to be less homogeneous than the radioactive one, but only by an amount to be expected from the experimental conditions (thick target etc.). Another such example is the disintegration

\[ ^{16}\text{B} + ^{2}\text{D} \rightarrow ^{11}\text{B} + ^{1}\text{H}, \]

in which Cockcroft and Lewis\(^{(7)}\) obtained a proton group of 90 cm. range, which appears to be homogeneous within \(\pm 4\) cm. The upper limit to any actual inhomogeneity set by this type of experiment is about \(\pm 20,000\) eV. This is much lower than the limit set by the cloud chamber experiments.

A more exact limit to the possible inhomogeneity cannot be obtained when the energy is determined by means of the range, because of the straggling. At present more precise methods, such as magnetic analysis, cannot be used because of the small intensities available.

We may however use the essentially similar process of \(\alpha\)-disintegration among the heavy radioactive elements. The groups of \(\alpha\)-particles emitted by say Ra C\(^{1}\) have been measured with great precision by magnetic analysis\(^{(20)}\). The apparent inhomogeneity is about \(\pm 10,000\) eV. and is completely accounted for by the geometrical conditions (slit-width). The actual inhomogeneity must therefore be much smaller than this. Any process leading to inhomogeneity, such as radiation, of interaction with the outer electron shells would be expected to be more active amongst the heavy nuclei.

\* The velocities being measured with respect to the centre of gravity of the system.

\† This has since been withdrawn\(^{(20)}\)
We come now to a problem where the breakdown of the conservation laws has been suggested in many quarters, and which has been extensively studied from this point of view.

A full discussion of the evidence on the \( \beta \)-ray spectra will be found in the \textit{Report of the International Conference on Physics} \textsuperscript{(21)} in 1934. Since then a considerable amount of theoretical and experimental work has been done which has made the situation much clearer, but there are still some features which require further study.

It has been known for a long time that the electrons emitted in \( \beta \)-ray disintegrations have a continuous distribution in energy. The experiments of Ellis and Wooster\textsuperscript{(22)}, and of Meitner and Orthmann\textsuperscript{(23)} established that the total energy emission, as detected in a calorimeter was given by the \textit{mean} energy of the \( \beta \)-rays. It followed that the \( \beta \)-rays were actually emitted from the nucleus with a continuous distribution in energy. On the other hand there was a good deal of independent evidence that nuclei of the same species were identical. In order to reconcile these two statements Bohr\textsuperscript{(24)} suggested that the conservation laws broke down in the \( \beta \)-ray disintegration (in a macroscopic way, cf. \textsection 1). On the other hand Pauli\textsuperscript{(25)} made the assumption that at each disintegration an uncharged particle, the "neutrino", was emitted which was able to pass out of the calorimeter (in the above experiments) without losing its energy.* The partition of the energy of disintegration between the electron, the neutrino and the residual nucleus, accounted for the continuous spectrum. Attempts to detect any ionization by the neutrino\textsuperscript{(26)} have failed, and the only evidence for its reality is its success in accounting for the facts of the \( \beta \)-ray disintegration.

On the neutrino theory the energy of disintegration should be equal to the \textit{maximum} energy of the \( \beta \)-ray spectrum (neglecting small corrections for the recoil of the nucleus, and the (undetermined) mass of the neutrino). Recent experimental work has mainly been concerned with testing this statement. To do this we must:

1. determine the energy of disintegration indirectly by (say) measuring the masses of the initial and final nuclei, or by using other disintegrations to determine this mass difference;
2. determine the end point of the \( \beta \)-ray spectrum.

This last is especially difficult because the spectrum has no abrupt end, but is found to approach zero intensity very slowly. If a reliable theoretical formula were known for the shape of the \( \beta \)-ray spectrum then this could be used to extrapolate the observed curves, and give an accurate value of the end point. The first theory making use of the neutrino hypothesis was put forward by Fermi\textsuperscript{(27)}, but the form of his \( \beta \)-ray spectrum was too symmetrical. The theory was modified by Konopinski and Uhlenbeck\textsuperscript{(28)}† in such a way as to remedy this. Their formula seems to give

* The neutrino was also given a spin \( \frac{1}{2} \hbar /2\pi \) in order to obtain conservation of angular momentum in the \( \beta \)-disintegration.

† Konopinski and Uhlenbeck introduced an interaction involving \textit{derivatives} of the wave function of the neutrino, i.e. depending on its \textit{velocity} as well as on its position. This does not seem to be capable of a simple physical interpretation, but is justified empirically by its results.
good agreement with the observed curves at least over the greater part of the distribution. However, extrapolations according to this theory lead to values of the end points which are generally beyond any energies actually observed, and are sometimes difficult to reconcile with indirect determinations of the disintegration energies.

*The end point of the continuous spectrum.* In the *Conference Reports* the identity of the end point with the disintegration energy was based on experiments on the double disintegration of ThC. The measurements of Henderson(20) on the end points of the β-ray spectrum of ThC and ThC" showed that if the end point did represent the actual energy release in the disintegration then the total energy released along the two branches

\[ \text{Th C'} \xrightarrow{\beta} \text{Th C'} \xrightarrow{\alpha} \text{Th D} \]

was practically the same, the figures being 11.20 MV. for the upper branch, and 11.19 MV. for the lower. However, if it were assumed that the actual energy releases are given by the mean β-ray energies, the two branches would still agree fairly well, because the β-ray spectra of Th C and Th C" are not very different. Using the mean energies given by Sargent(30) we obtain 9.75 MV. along the upper branch and 9.98 MV. along the lower, a discrepancy which is not large enough definitely to exclude this hypothesis.

Experiments on the artificial radioactive elements lead to more definite evidence on this point. In some recent papers in the *Physical Review*(31,32) the form of the β-ray (or positron) distribution has been determined for a number of elements. The curvatures of the tracks in a Wilson chamber in a magnetic field were measured. The distribution curves obtained were compared with the Konopinski-Uhlenbeck theory (see above) and give a satisfactory agreement. The end points determined by inspection and by extrapolation were compared with indirect determinations of the disintegration energy. These calculations are given here with changes arising from some recent redeterminations of the quantities involved.

The two radioactive elements *Li and 12B have spectra extending up to about 10 MV. and therefore provide an excellent test of whether the mean or the maximum of the spectrum is equal to the disintegration energy, since the maximum is about 7 MV. greater than the mean. This advantage is set off by the uncertainty in the interpretation of the experiments.

*The Element.* *Li. Crane, Delsasso, Fowler and Lauritsen(33) observed the emission of high energy electrons when lithium targets were bombarded with deuterium ions. They ascribed these to the formation of the unstable element *Li by the reaction

\[ ^7\text{Li} + ^2\text{D} \rightarrow ^8\text{Li} + ^1\text{H} + Q_1 \] \hspace{1cm} \text{......(1).}
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The half-period was found to be 0.5 sec., the disintegration probably being either

\[ ^{8}\text{Li} \rightarrow ^{8}\text{Be} + e^- \quad \cdots \quad (2), \]

or

\[ ^{8}\text{Li} \rightarrow 2^4\text{He} + e^- \quad \cdots \quad (3). \]

The difference in energy emission between these two would be only slight, since \(^{8}\text{Be}\) is known to have nearly the same mass as two \(\alpha\)-particles.

In order to obtain the mass of \(^{8}\text{Li}\) it is necessary to observe the protons in reaction (1). This is difficult since they are masked by the protons from

\[ ^{6}\text{Li} + 2^2\text{D} \rightarrow ^{7}\text{Li} + ^{1}\text{H} \quad \cdots \quad (4). \]

Delsasso, Fowler and Lauritsen\(^{14}\) have reported a group of protons of 26 cm. range of about the right intensity, besides the 30 cm. group from reaction (4).\(^*\) If reaction (1) takes place at all, the protons must have a range less than 30 cm., or they would have been observed in previous experiments. From these considerations we may put \(Q_1\) certainly less than 4.3 MV.

Comparing this with the reaction

\[ ^{7}\text{Li} + 2^2\text{D} \rightarrow ^{8}\text{Be} + 1n + 14.3 \text{ MV.} \quad \cdots \quad (5).^{13} \]

or

\[ ^{7}\text{Li} + ^{1}\text{H} \rightarrow 2^4\text{He} \quad \cdots \quad (6),^{13} \]

we find that the energy release in the disintegration of \(^{8}\text{Li}\) according to (2) or (3) must be at least 10-2 MV. This figure agrees with the observed upper limit to the spectrum and cannot be reconciled with the average \(\beta\)-ray energy which is only about 3.5 MV.

The element \(^{12}\text{B}\). Very similar considerations apply to the other short period element obtained by Crane etc., \(^{12}\text{B}\). This is supposed to be formed by the reaction

\[ ^{11}\text{B} + 2^2\text{D} \rightarrow ^{12}\text{B} + ^{1}\text{H} \quad \cdots \quad (7). \]

However, a careful search for these protons has been made by Cockcroft and Lewis\(^7\) who could not find any group of sufficient intensity beyond 2 cm. range. Disregarding this difficulty, a similar comparison may be made (assuming a very low energy for the protons) and the result is again, that the energy of disintegration must be the maximum and not the mean energy of the \(\beta\)-rays.

Positron emission \(^{13}\text{N}\). We turn now to some cases of positron emission, to which the same theoretical considerations apply. A much discussed disintegration is that of \(^{13}\text{N}\). Although the positrons have only a comparatively low energy, the quantities involved have been measured accurately, so that a fairly severe test of the conservation principle can be obtained.

The calculations have been made by a number of workers including Cockcroft and Lewis\(^7\), Tuve and Hafstad\(^{15}\), and Newson\(^{27}\). They are given here with the latest available data. The method is to compare the three reactions

\[ ^{12}\text{C} + 2^2\text{D} \rightarrow ^{13}\text{N} + 1n + Q_8 \quad \cdots \quad (8), \]

\[ ^{12}\text{C} + 2^2\text{D} \rightarrow ^{13}\text{C} + ^{1}\text{H} + Q_9 \quad \cdots \quad (9), \]

\[ ^{18}\text{N} \rightarrow ^{18}\text{C} + e^+ + Q_{10} \quad \cdots \quad (10). \]

* Recent experiments\(^{57}\) with separated isotopes have shown that this new group actually belongs to reaction (4) and not to (1). The protons predicted by equations (1) and (7) have not been found despite careful searches. This reduces considerably the value of any argument based on the existence of \(^{8}\text{Li}\) and \(^{12}\text{B}\).
Clearly we should have
\[ Q_{10} = q_s - q_8 - (n - H) - (\epsilon^- + \epsilon^+) \] .......(11).

Bonner, Delsasso, Fowler and Lauritsen give \( q_s = -0.37 \pm 0.03 \text{ MV} \).

Cockcroft and Lewis state that \( q_s > -0.32 \text{ MV} \).

We may adopt the value \( q_s = -0.32 \text{ MV} \).

For \( q_s \) there are three accurate determinations.

Cockcroft and Lewis give \( 2.66 \pm 0.02 \text{ MV} \).

Bonner, Delsasso, Fowler and Lauritsen give \( 2.65 \pm 0.07 \text{ MV} \).

Bainbridge and Jordan by an accurate determination of the doublet separation \( ^{12}\text{C} + ^1\text{H} \rightarrow ^{13}\text{C} \) gives \( 2.76 \pm 0.1 \text{ MV} \). This is important because it excludes the possibility of a high energy \( \gamma \)-ray emission in reaction (9). The mass of the neutron is best obtained from Feather and Bretscher's work on the photo disintegration of the deuteron, which together with Aston's mass for the latter gives
\[ n - H = 0.83 \pm 0.05 \text{ MV} \.

Combining these values we obtain from equation (11)
\[ Q_{10} = 1.13 \pm 0.15 \text{ MV} \.

The maximum energy of the positrons from \( ^{13}\text{N} \) has been determined by many workers; the values obtained are generally somewhat higher than the above. Thus Fowler, Delsasso and Lauritsen give a distribution which appears to end at \( 1.25 \text{ MV} \), but when extrapolated according to the theory of Konopinski and Uhlenbeck, gives an end point at \( 1.45 \pm 0.1 \text{ MV} \). Kurie, Richardson and Paxton obtained almost the same result. Alichanow, Alichanian and Dzelepow give a curve ending at \( 1.45 \text{ MV} \), and Cockcroft, Gilbert and Walton one at \( 1.1 \text{ MV} \).

These values mostly agree with the predicted value within the possible errors, although the discrepancy in the case of the extrapolated end point of \( 1.45 \text{ MV} \) is large enough to throw some doubt on the Konopinski-Uhlenbeck theory.

The element \( ^{17}\text{F} \). This element has been formed in two ways which we will consider separately.

The reaction \( ^{16}\text{O} + ^2\text{D} \rightarrow ^{17}\text{F} + ^1\text{H} + Q_{12} \) .......(12), has been studied by Newson. From the excitation curve he obtains
\[ Q_{12} > -1.8 \text{ MV} \.

The \( F_{17} \) disintegrates according to the equation
\[ ^{17}\text{F} \rightarrow ^{17}\text{O} + Q_{13} \] .......(13),

and this may be compared with
\[ ^{16}\text{O} + ^2\text{D} \rightarrow ^{17}\text{O} + ^1\text{H} + Q_{14} \] .......(14).

As before
\[ Q_{13} = Q_{14} - (n - H) - (\epsilon^- + \epsilon^+) \).

Cockcroft and Lewis give \( Q_{14} = 1.91 \text{ MV} \), which leads to \( Q_{13} \leq 1.9 \text{ MV} \).

* \( \epsilon^- \) and \( \epsilon^+ \) stand for the (equal) masses of the positive and negative electrons. The presence of \( \epsilon^- \) in equation (11) arises from the unfortunate convention of inserting, not the nuclear masses, but the masses of neutral atoms, in these equations.

† The experiment reported by Ising and Helde leads to \( (n - H) = 0.4 \text{ MV} \), but this is almost certainly incorrect.
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The observed distribution curve extends to 2.1 MV. According to the Kono-pinski-Uhlenbeck theory it ends at 2.4 MV, so that here again too high a value is obtained.

The same active element is formed by the reaction

\[ ^{14}\text{N} + ^{4}\text{He} \rightarrow ^{17}\text{F} + ^{1}\text{n} + Q_{15} \quad \cdots \cdots (15). \]

According to Haxel the excitation of neutrons starts at an \( n \)-particle energy of 5.9 MV, which leads to \( Q_{15} = -4.6 \) MV.

Using the reaction

\[ ^{14}\text{N} + ^{4}\text{He} \rightarrow ^{17}\text{O} + ^{1}\text{H} + Q_{16} \quad \cdots \cdots (16), \]

with \( Q_{16} = -1.3 \) MV.

we obtain

\[ Q_{13} = Q_{18} - Q_{15} - (n - H) - (e^- + e^+) = 1.5 \text{ MV}. \]

which is in still worse agreement with the experimental value. The deduction of energy changes from excitation curves is not very reliable, but the results can hardly be in error by as much as 1 MV.

**The element \(^{30}\text{P}^\text{.}** The energy balance in the disintegration of \(^{30}\text{P}^\text{.} has been discussed by Ellis and Henderson. They found that the maximum positron energy was 2.9 MV. This result can be compared with the data for the two reactions

\[ ^{27}\text{Al} + ^{4}\text{He} \rightarrow ^{30}\text{Si} + ^{1}\text{H} + Q_{17} \quad \cdots \cdots (17) \]

\[ ^{27}\text{Al} + ^{4}\text{He} \rightarrow ^{30}\text{P}^{3} + ^{1}\text{n} + Q_{18} \quad \cdots \cdots (18), \]

\( Q_{17} \) has been determined as 2.07 MV, by Duncanson and Miller. \( Q_{18} \) was determined by Jaeckel, from the recoil tracks produced by the neutrons in a cloud chamber. From his measurements \( Q_{18} = -2.3 \) MV. He states that this is likely to be an underestimate but actually all his evidence of high energy neutrons was obtained from protons projected at large angles to the neutron beam, and is therefore unreliable. By comparing equations (17) and (18) we obtain 2.55 MV, as the predicted maximum positron energy. The probable error in this is difficult to estimate but it is at least 0.4 MV., so that the difference between this and the experimental figure is not serious.

The above five elements are the only ones for which data of any accuracy are available, the results are collected in the following table.

<table>
<thead>
<tr>
<th>Element</th>
<th>+ or − active</th>
<th>Energy change (MV.) from other disintegrations</th>
<th>Observed end point</th>
<th>K−U end point</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{8}\text{Li}^\text{.}</td>
<td>−</td>
<td>&gt; 10.2</td>
<td>10 MV.</td>
<td>11.2 MV.</td>
</tr>
<tr>
<td>(^{12}\text{B}^\text{.}</td>
<td>−</td>
<td>&gt; 12.1</td>
<td>11.5</td>
<td>13.0</td>
</tr>
<tr>
<td>(^{13}\text{N}^\text{.}</td>
<td>+</td>
<td>1.13 ± 0.15</td>
<td>1.45 ± 0.15</td>
<td>2.4</td>
</tr>
<tr>
<td>(^{17}\text{F}^\text{.}</td>
<td>+</td>
<td>&lt; 1.9, &lt; 1.5</td>
<td>2.9 ± 0.1</td>
<td>2.4</td>
</tr>
<tr>
<td>(^{30}\text{P}^\text{.}</td>
<td>+</td>
<td>2.55 ± 0.4</td>
<td>2.55 ± 0.4</td>
<td></td>
</tr>
</tbody>
</table>

* Since this was written Bonner and Brubaker have given similar calculations for the element \(^{12}\text{C}^\text{.}
It will be seen that although the energy of disintegration is certainly not given by the mean particle energy, the accuracy with which it can be equated to the maximum is not very great. The end point of the spectrum found by inspection gives a fair agreement with the energy of disintegration as determined indirectly from other disintegrations, and within the experimental error these may be identified. On the other hand the end point obtained by extrapolation on the Konopinski-Uhlenbeck theory appears to be rather too high: this throws doubt on the method of extrapolation. Thus we may regard the neutrino hypothesis as justified by the agreement between the end point and the disintegration energy, but the form of the spectrum near the end point is not yet given correctly by the theory.

We may mention as a further possible method of confirming the neutrino theory, the experiment carried out by Leipunski. By a very ingenious method he succeeded in measuring the velocity of the atoms recoiling when radioactive disintegrates. He found that the velocity was considerably greater than would be expected from the ejection of the electron alone, and ascribes the extra velocity to the ejection of the neutrino. The maximum velocity of recoil should be no greater with a neutrino than without. In both cases it occurs when the electron is ejected with all the available energy, leaving the neutrino, if it exists, at rest. The presence of the neutrino may however cause an increase in the average velocity of recoil. This seems to be indicated by Leipunski's curve. Further work on these lines should lead to more definite results.

§ 4. THE INTERACTION OF RADIATION AND MATTER

The question of whether the conservation of energy and momentum holds in detail, or only statistically for processes involving radiation has been a centre of a controversy during the past year which is a curious repetition of one which took place in 1924. Owing to the difficulty at that time of reconciling the photon theory of light with the electromagnetic theory, Bohr, Kramers, and Slater proposed a less crude application of the particle conceptions to radiation problems.

In terms of this theory one may picture a typical process of radiation as follows. In the disintegration

\[ ^{10}\text{B} + ^{4}\text{He} \rightarrow ^{13}\text{C} + ^{1}\text{H} \]

the \(^{13}\text{C}\) nucleus is sometimes left in an excited state. It subsequently reaches the ground state by emitting a \(\gamma\)-ray. The mean life \(\tau\) of the \(^{13}\text{C}\) nucleus in this excited state is extremely short, \(10^{-12}\) sec. Thus within \(10^{-12}\) sec. of the emission of the proton, a quantum will be emitted which may be recorded by a Geiger counter if it gives rise to a secondary electron inside it. This is the particle picture. According to the Bohr-Kramer Slater theory the nucleus is a source of radiation which decays exponentially according to the law \(e^{-t/\tau}\). This radiation falls on the counter and

* An agreement between the extrapolated end point of the \(\beta\)-ray spectrum, and the disintegration energy is sometimes said to prove that the mass of the neutrino is zero or very small. Dr Peierls has pointed out to the author that this is incorrect. The insertion of a finite neutrino mass in the Konopinski-Uhlenbeck theory modifies the extreme end of the spectrum so that an extrapolation such as that used in these experiments no longer gives the end point of the spectrum, but still gives the true disintegration energy (i.e. including the neutrino mass).
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gives rise to a certain probability, that a secondary electron will be ejected and a count recorded. This probability is quite independent of whether any other secondary electron has been ejected by the same source of radiation, or whether the $^{12}$C nucleus has yet fallen to its ground state (although this fall is not "observable"). Apart from this the predictions of the Bohr Kramer Slater theory are just the same as the particle theory. In practice $\tau$ is always extremely short, at least for phenomena where the individual acts of radiation can be detected, and so within experimental limits on either theory there should be coincidences between the emission of the proton and of the discharge of the Geiger counter. This is found to be so in practice.$^{(49)}$

This agreement disappears when we consider the Compton effect, because here two secondary processes, recoil electron and scattered quantum (detected as photo electron) follow from the same primary process. The "photon" theory of the Compton effect is well known, it leads to certain equations between the angles of projection $\theta$, $\phi$ of the scattered quantum and the recoil electron, and the energies of these particles, and of course the two secondary processes happen simultaneously.

As applied to the Compton effect the Bohr Kramer-Slater theory on the other hand proposed that a volume element containing a certain density of electrons, and irradiated by the primary beam, had a certain probability per unit time of ejecting a recoil electron in any direction $\theta$. (The electron would have the energy corresponding to this direction.) Also there was a certain probability that somewhere along a direction $\phi$ a photo electron would be ejected, corresponding to the scattered quantum.

Here also the relation between the energy of the photo-electron and the angle $\phi$ was left untouched. The theory however regarded these two probabilities as quite independent, it denied that the two events (recoil electron, photo-electron) were simultaneous except by chance, and that the relation given by the particle theory between the angles $\theta$, and $\phi$ was valid.*

This theory agreed with all the facts which were known at that time. It was tested: (1) by Bothe and Geiger$^{(50)}$ who detected the scattered electron in one Geiger counter, and the photo-electron in another, and found coincidences in time between the discharges of the counters. (There was no test of the relation between $\theta$ and $\phi$ since the scattering took place inside the electron counter.) (2) by Compton and Simon$^{(51)}$ who introduced a beam of X rays into a cloud chamber where the scattering took place. They were able to see the track of the recoil electron, and in some cases also the photo-electron ejected from some lead plates by the scattered quantum. They were therefore able to verify the relation between $\theta$ and $\phi$. Both

* In the absence of any correspondence between the individual recoil electrons and photo-electrons, the angular conditions necessarily fail. The above description of the theory is correct if the primary beam is considered as a continuous radiation field. Difficulty is sometimes found in seeing that the same result also follows even when the primary radiation is regarded as made up of separate pulses (e.g. from individual electrons arriving at the anti-cathode of the X-ray tube). It is true that both the scattered electron and photo-electron have to coincide with such a pulse, but this does not ensure coincidences of the two. Suppose the counter detecting recoil electrons responds to one pulse in every $10^{16}$ and the quantum counter to one in $10^{15}$. Then if, as on the B.K.S. theory, the counters "choose" their pulses at random and independently, there is little chance of their choice coinciding.
these experiments were of great technical difficulty, but the results were sufficiently
definite to disprove the B. K. S. theory.

The first of the recent repetitions of the Bothe-Geiger experiment was that of
Shankland, (52) which led to the conclusion that the particle theory was incorrect. As
a source of radiation Shankland used a tube containing radon (100 mg.) in equili-
branch with its products. After being collimated by a long hole in a block of lead
the γ-rays struck the target, for which various materials were used. The recoil
electrons and the scattered γ-rays were detected by two systems of counters which
were protected from the primary beam and from "stray" scattering by means of
lead shields. For the scattered γ-rays five counters were used in line, thus increasing
the chance of recording the γ-ray quantum by a factor of five (but also increasing
the natural count five times).

The recoil electrons were also detected by tube counters; two used as a coin-
cidence counter in one experiment and one alone in another. These counters were
set to detect particles coming at definite angles, generally 35° to the primary beam
for the electrons.*

The number of coincidences due to chance was calculated from the observed
rates of counting in the individual counters and the resolving time, the latter
having been determined previously by finding the number of coincidences when the
counters were discharged by a radium source.

In the actual experiment it was found that the observed number of coincidences
only slightly exceeded the number due to chance, the difference being much lower
than that expected from the particle theory. Further no more coincidences were
observed when the counters were placed in positions where the coincidences would
be expected, than when one of the counters was rotated out of the plane formed by
the primary beam and the other counter, when on the particle theory no coin-
cidences should occur.

Thus with a paraffin scatterer 0.05 cm. thick Shankland obtained \(14 \pm 3\) coin-
cidences per hour, compared with an expected number of 69 on the photon theory,
and 9 due to chance. When one of the counters was rotated through 90° about the
primary beam, the observed number of coincidences was still \(12 \pm 4\) per hour.

From these results Shankland concluded that the particle theory was incorrect.
Before passing to other experiments we may notice that the whole argument depends
on the correctness of the predicted number of coincidences. If this were smaller
by a factor of ten, it would hardly be detected in these experiments. Other workers
using the more homogeneous Th C\(^{11}\) γ-rays, have generally found that the actual
number of coincidences fell short of that expected from the geometry by a large
factor. This discrepancy is principally due to inhomogeneity in the γ-ray beam, and
to scattering of the recoil electrons in the target. It is difficult to judge how im-
portant these factors were in Shankland's experiments, but it is probably along
these lines that an explanation of his results must be sought.

* The angle for which the γ-ray counter was set is not given, it appears to be about 80° on
the diagram. This would lead to coincidence for a primary quantum energy of about 500,000 eV.
The angular conditions are not sharp and quanta between 250,000 and 800,000 eV. might give
coincidences. This illustrates the difficulties caused by using an inhomogeneous source; there is
no definite angle at which the counters should be set.
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The publication of Shankland's results was followed by many speculations on their interpretation, for instance whether the contradiction between his results and those of Bothe and Geiger was due to the use of γ-rays or to the test of angular conditions as well as simultaneity. This discussion need not be gone into now in view of the results obtained in other experiments.*

Among the later experiments supporting the particle theory, which have been reported briefly, we may take those of Bothe and Maier-Leibnitz for discussion. They used a source of radio thorium (20 mg.), the γ-rays from which are much more homogeneous than those from Ra (B + C). They used a thin scatterer of celophane, and one counter each for the electrons and scattered quanta set so as to detect particles coming at an angle of 30° with the primary beam.

The presence of the scatterer increased the number of counts in the electron counter by a factor of two, from 45 per min. to 85 per min., but made no appreciable difference to the quantum counter (40 per min.) owing to its much lower efficiency. The coincidences numbered 25 in $14\frac{1}{2}$ hours. The number of these due to chance was determined by removing the scatterer and bringing the number of electron counts up to the same number as with the scatterer by means of a radium D source. (This method of determining the chance coincidences, by doing a "control" experiment under the same conditions as the actual experiment is more satisfactory than calculating the chance coincidences from the resolving time of the circuit.) In this way it was found that 20 of the 25 coincidences were genuine.

Bothe and Maier-Leibnitz also tried the effect of rotating one of the counters through 90° about the primary beam, when the number of coincidences fell to 9 ± 8. In another experiment they moved the scattering foil along the primary beam so as to bring $\theta$, $\phi$ to values for which coincidences would not be expected on the particle theory, when the number of genuine coincidences again fell off.

A comparison of the number of observed coincidences with the number expected on the photon theory shows that the observed number is much too small, unless corrections due to the scattering of the recoil electrons inside the target, and inhomogeneity of the primary γ-rays is taken into account.

Similar experiments with a thorium source have been reported by Jacobsen, these also led to the conclusion that the coincidences were real.

In view of these results, there can now be little doubt of the correctness of a description of the Compton effect along the lines of the photon theory, as a discrete event involving particles, and the Bohr Kramers and Slater theory must be rejected. There is still however the difficulty of accounting for the negative result of Shankland's experiments.†

§ 5. ACKNOWLEDGMENT

In conclusion the author wishes to thank Prof. C. D. Ellis for the many helpful suggestions and criticisms he has made during the preparation of this report.

* It was shown by Williams at this stage that Shankland's results were not in accord with the Uncertainty Principle.

† Since the above was written a great deal more evidence has accumulated in favour of this view. We may mention Shankland's own extension of his experiment, a repetition of the Compton-Simon experiment, and an ingenious experiment by Williams and Pickup all of which support the particle picture of the Compton process.
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