The Coincidence Method

Walther Bothe - Nobel Lecture*

Before embarking on the subject of my lecture, permit me to devote a few words to the man to whom, apart from my teacher, Max Planck, I owe so much, and who died ten years ago after a long period of painful suffering. In 1912 Hans Geiger was appointed Director of a new Laboratory for Radioactivity at the Physikalisch-Technische Reichsanstalt, Berlin-Charlottenburg of which Emil Warburg was then the President; previous to this, he had worked for six years under Rutherford at Manchester. In June 1913, I became Geiger's assistant. The Laboratory for Radioactivity consisted of only two rooms at the time; at a later date, when tests of radioactive substances became more extensive, it expanded into four rooms. This modesty of his room requirements - Geiger repeatedly stated that he had no desire for a giant institute - is characteristic of the principal trait in Geiger's personality as a scientist: the desire to keep scientific work within economic bounds. No doubt, the unique influence of Rutherford had something to do with this; equally indubitably, this influence harmonized with a natural tendency. However this may be, the experiments by Geiger and Marsden on the scattering of alpha rays are known to form part of the beginning of the entire experimental atom physics of recent days. I think the main lesson which I have learnt from Geiger is to select from a large number of possible and perhaps useful experiments that which appears the most urgent at the moment, and to do this experiment with the simplest possible apparatus, i.e. clearly arranged and variable apparatus.

It was in 1924 that I came across the theoretical paper by Bohr, Kramers, and Slater, which had just been published and which suggested a possible interpretation of the wave-particle dualism in the accepted description of the properties of light. This must be understood to mean the experimental fact that light of all wavelengths behaves as a wave process (interference) with pure propagation, but behaves as particles (light quanta: photo-effect, Compton effect) on conversion into other types of energy. The new idea consisted in denying strict validity to the energy-impulse law. In the individual or elementary process, so long as only a single act of emission was involved, the laws of conservation were held to be statistically satisfied only, to become valid for a macroscopic totality of a very large number of elementary processes only, so that there was no conflict with the available empirical evidence. It was immediately obvious that this question would have to be decided experimentally, before definite progress could be made. That such a decision was possible, Geiger and I agreed immediately, when I discussed the paper by Bohr, Kramers, and Slater with Geiger.

The experimental problem offered several means of attack. We decided in favour of an experiment with the effect discovered a short time previously by A.H. Compton, i.e. the scattering of light on practically free electrons. Apart from the scattered light, there occur the "recoil electrons" which had been observed and interpreted by C.T.R. Wilson in the cloud chamber, and by me both in the cloud chamber and by an ionization method. The "question to Nature" which the experiment was designed to answer could therefore be formulated as follows: is it exactly a scatter quantum and a recoil electron that are simultaneously emitted in the elementary process, or is there merely a statistical relationship between the two?

Meanwhile, Geiger had developed the so-called needle counter which has the advantage of responding not only to heavy particles but also to electrons, and therefore to light quanta of sufficiently high energy capable of releasing electrons within the counter.

Our arrangement therefore consisted of two needle counters, past the common front wall of which, without touching it, swept a beam of X-rays. The X-ray beam travelled in a hydrogen atmosphere; the Compton processes occurred in the one counter which indicated the recoil electrons, whereas only the scatter quanta were able to penetrate into the other counter and actuated it by electron release with very much lower probability. The readings of both counters were recorded side by side on a moving paper chart. In this way we succeeded after a few failures to establish the accuracy of any temporal "coincidence" between the two pointer readings as being 10-4 sec. Film consumption however was so enormous that our laboratory with the film strips strung up for drying sometimes resembled an industrial laundry.

The final result we obtained was that systematic coincidences do indeed occur with the frequency that could be estimated from the experimental geometry and the response probabilities of the counters on the assumption that, in each elementary Compton process, a scatter quantum and a recoil electron are generated simultaneously. The strict validity of the law of the conservation of energy even in the elementary process had been demonstrated, and the ingenious way out of the wave-particle problem discussed by Bohr, Kramers, and Slater was shown to be a blind alley.

This result was confirmed by different researchers using various experimental arrangements. When, more than ten years later, some doubts as to the correctness of this result were voiced, I tried with my then assistant, H. Maier-Leibnitz, to supplement and improve the original experiment in one point: the object was to demonstrate both simultaneity and uniformity of direction of scatter quantum and recoil electron, as was to be expected according to Compton's theory, i.e. according to the laws of elastic impact between two bodies. On this occasion, we employed the energy-rich gamma radiation of a radiothorium preparation. Again, the result was clearly positive. This demonstrated both the conservation of energy and the conservation of the impulse.

Unfortunately, the collaboration with Geiger came to an end in 1925, when Geiger was called to Kiel University. When dividing up the field on which we had hitherto worked together, the coincidence method was, at Geiger's generous suggestion, allocated to me.

The possibility of the purely statistical validity of the conservation theorems discussed by Bohr, Kramers, and Slater appeared sufficiently important to be tested in yet another case. A spherical wave is emitted in the elementary process of light emission. The problem was: can this spherical wave initiate an absorption act in one direction of emission only, as the energy theorem postulates, or can it do so also statistically independently in several directions, as is to be expected according to Bohr, Kramers, and Slater? It must be borne in mind in an experiment of this kind, that, by contrast with the Compton effect, the probability of demonstrating an absorption act may not be of an order of magnitude much below unity, because otherwise any systematic coincidences that might occur would be submerged in the inevitable accidental coincidences. This was achieved by harmonizing the radiation source (iron or copper-K-fluorescence radiation) and the gas charge of the needle counters (argon) erected on either side so that the absorption probability in the gas charge was as close as possible to unity. Besides, the solid angles which the two counters offered to the radiation source had to amount as far as possible to 2 p. The result of this experiment (1926) was that no systematic coincidences occurred, at least not with the frequency to be expected according to Bohr, Kramers, and Slater. Strict conservation of energy in the elementary process had thus been confirmed also by a negative experiment. The wave-particle problem was destined to remain open for a short time only. During this time I had the singular good fortune of being able to discuss the problem constantly with Einstein. Some experiments done at Einstein's suggestion yielded no decisively new result. The (at least formal) solution was provided by wave mechanics; it is contained simply in the assumption that the Schrdinger wave of a system consisting of n particles is a wave in the 3n-dimensional "configuration space".

An entirely different field in which the coincidence method bore fruit, was that of "cosmic radiation" or "ultra radiation" as its discoverer, Hess, called it. Meanwhile, Geiger had developed, in Kiel, the powerful tool of the Geiger-Mller counter. Coincidences between unscreened counters, caused by cosmic rays, had been observed both by Geiger himself and by W. Kolhrster, then a guest in my Berlin laboratory. More profound discoveries were to be expected by arranging absorbing layers of variable thickness between or/and above the counters. Such experiments which I conducted together with Kolhrster in 1929 prompted the daring conclusion that cosmic radiation does not consist primarily of gamma rays, as had generally been assumed previously because of the high permeating power, but of material particles with an energy of at least 1,000 million electron volt. Such countercoincidence arrangements were increasingly used in the period which followed, using increasing numbers of counters, in part combined with cloud chambers, ionization chambers, scintillation counters, etc. The material particle nature of primary cosmic radiation has been confirmed, although the processes turned out to be extraordinarily more complicated than we had assumed. As a simple example of this we would only mention that B. Rossi who also spent some time as guest in my PTR laboratory, later succeeded in observing by means of coincidences between juxtaposed counters ("Rossi curve”) the first signs of the occurrence of showers of particles. The possible applications of the coincidence method to the subject of cosmic radiation have by no means been exhausted yet.

The same principle of measurement as in cosmic radiation can of course also be applied to ordinary beta and gamma rays. It is for example possible to determine in a very simple manner, with the assistance of only two counters and a variable absorber between them, the mean gamma energy in a mixture of gamma rays and their secondary electrons (Bothe and Becker, 1930). This method can be useful where for some reason it is impossible to apply the usual spectrometer method with magnetic deviation.

The technology of coincidence counting has been considerably improved meanwhile. Instead of the complicated photographic recording, we have long since passed on to valve circuits in conjunction with mechanical counters, which provides the advantage of greater simplicity and permits reduction of the so-called resolution period by several orders of magnitude, so that the interfering ”accidental” coincidences in many cases play no part at all. I used a circuit employing a multiple-grid coincidence valve as early as 1929. Rossi was the first to describe another system working with valves in parallel; it has the advantage that it can easily be extended to coincidences between more than two events, and is therefore predominantly used today. (Recently, Z. Bay and others succeeded, in the U.S.A., in reducing the coincidence resolution period to 10-11 sec by means of multipliers.)

A further large field for the application of the coincidence method is that of nuclear reactions. In a joint investigation with my collaborator H. Frnz (1928) and Pose in Halle it was discovered that in the artificial conversion of a nucleus (10B in our case) by alpha rays, there occur several discrete proton groups of different energy. Shortly afterwards (1930) I discovered, with H. Becker, the gamma rays that are generated on bombarding not only boron, but also other elements, with alpha rays. Both these results found a common interpretation. During conversion, the newly formed nucleus is not always immediately in the ground state, but is at times in one of the possible activated states. In this case, the particle formed has correspondingly less energy, whereas the product nucleus passes into the ground state with emission of the quantity of energy saved as gamma radiation. As a rule, this transition occurs in a period of immeasurably short duration, i.e. practically simultaneously with the emission of the new particle. To demonstrate this simultaneity is by no means trivial, because it may for example happen that the product nucleus always forms in an activated state at first. This can be decided by coincidence measurements. In this case, even the most energyrich group of particles that occurs would have to be coupled with gamma radiation, which is not the case if this group belongs to the ground state of the product nucleus. (For the case of ”metastable” states of excitation, these arguments must be modified analogously.) Such measurements were first carried out in 1925 by H.J. von Baeyer who was then my student at Heidelberg, again for the case, already mentioned, of boron conversion by alpha rays. In the same manner, it is possible to determine whether two or several of the gamma quanta generated in a nuclear reaction form in the same nucleus, i.e. practically simultaneously, or whether they are emitted alternatively during the conversion of separate nuclei. Such questions are of importance for the balance of energy, i.e. for the measurement of reaction energies and nuclear mass. Direction coupling between the various radiations generated in a nuclear reaction both with one another and with the initiating radiation can also be detected and measured by coincidences; this provides valuable information about the structure of the atomic nuclei. Analogous problems in spontaneous conversions (natural and artificial radioactivity) can be tackled experimentally in the same manner, as has been demonstrated with RaC decomposition (Bothe and Maier-Leibnitz, 1937).

Many applications of the coincidence method will therefore be found in the large field of nuclear physics, and we can say without exaggeration that the method is one of the essential tools of the modern nuclear physicist.

* Owing to Professor Bothe's illness the lecture was not given orally.

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