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Coincidence Method

W. Bothe

Before starting with my actual theme, may I be permitted to remember with a few words the man to whom, besides my teacher, Max Planck, I owe so much, and who died 10 years ago after a long and agonizing illness, Hans Geiger.

In the year 1912, Hans Geiger was called as director of the Laboratory for Radioactivity which was then to be newly established at the Physikalisch-Technische Reichsanstalt in Berlin-Charlottenburg under Emil Warburg's presidency. During the 6 years before joining the Reichsanstalt, Geiger worked in Manchester in Rutherford's Laboratory.

In June 1913, I became Geiger's assistant. At that time, the Laboratory for Radioactivity consisted of two rooms only. Later, when the number of measurements of radioactive substances increased considerably, it was enlarged to four rooms. Already this modest demand for space—Geiger repeatedly stated that he did not want a giant institute—is typical of the whole character of Geiger's scientific personality: the endeavor for economy in scientific work. This was to some extent certainly due to the unique influence of Rutherford, but it is equally certain that this influence met with his own natural outlook.

Certainly everybody recognized that the experiments by Geiger and Marsden on the scattering of alpha particles are the basis of all the recent development in experimental, atomic, and nuclear physics. Mainly, I think, I learned from Geiger always to select from a large number of possible and useful experiments the one which at the time appeared to be the most important and to execute this experiment with simple equipment, which was versatile and adaptable also to other problems.

In the year 1924, I came upon the theoretical paper by Bohr, Kramers, and Slater that had just been published. In this paper the authors point to a possibility to understand the dualism (wave-corpuscle) in the then current description of the properties of light. One has to understand the experimental fact that light of all wavelengths, as far as pure propagation is concerned, will behave like a wave (interference effects). However, if light is converted into a different form of energy, it behaves like a particle (light quanta: photo effect, Compton effect). The new idea was to deny the strict validity of the law of conservation of energy and momentum. In the single or elementary process, as long as a single emission only is taking place, the conservation laws should be fulfilled statistically only. For a macroscopic ensemble of many elementary processes, however, the conservation laws were supposed to be valid.

Thus there was agreement and no discrepancy with the then known experimental facts. It was at once quite clear that this question had to be decided by experiment before reliable progress could be made. That such an experimental decision is feasible was completely agreed upon by Geiger and myself as soon as we discussed the paper by Bohr, Kramers, and Slater.

Experiments with the Compton Effect

The experimental problem could be approached in various ways. We decided on an experiment about the Compton effect discovered somewhat earlier—namely, the scattering of light on practically free electrons. Besides the scattered light, there appear also the recoil electrons, which were observed by C. T. R. Wilson in a cloud chamber, and which I observed, both with a cloud chamber and with an ionization method, and recognized as recoil electrons. The question posed to nature that had to be answered experimentally was therefore: In the elementary process each time that a quantum is scattered and an electron recoils, are the two simultaneous or is there only a statistical coupling between the two? In the meantime, Geiger developed the so-called "point counter." This has the advantage of being sensitive, not only to heavy particles, but also to electrons and, therefore, also to light quanta of energy high enough to be able to release electrons in the interior of the counter.

Our arrangement consisted, therefore, of two point counters with a common frontpiece over which an x-ray beam passed without striking it. The x-ray beam passed through a hydrogen atmosphere. The Compton processes occurred in the interior of one of the counters, which registered the recoil electrons. In the other counter only scattered light quanta could penetrate and were registered with a much smaller probability by the secondary electrons released through the quanta. The pulses from the two counters were registered side by side on a movable paper film. In this way we were able, after a few unsuccessful attempts, to determine whether or not the two events were coincident within a time interval of 10^{-4} second or less. The amount of film used was so large that when the films were hung up to dry our laboratory gave the impression of a giant commercial laundry.

The final result was that actually systematic coincidences appeared with a frequency that could be expected from the experimental geometry and the detection efficiencies of the counters, assuming that in each elementary Compton process one scattered quantum and one recoil electron are produced *simultaneously*. The strict validity of the law of the conservation of energy even in the

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elementary process was thus proved, and the ingenious idea to solve the wave-corpuscle problem, as discussed by Bohr, Kramers, and Slater, was shown to be incompatible with the experiment.

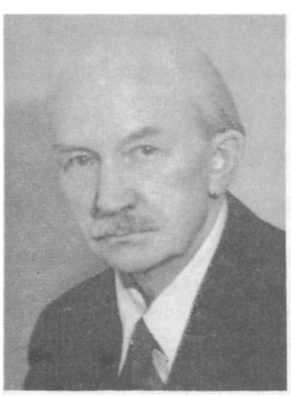
This result was confirmed by several investigators using different experimental arrangements. When, after more than 10 years, some doubt was raised concerning the validity of these results, I tried with H. Maier-Leibnitz—then my collaborator—to improve and supplement the original experiment in one point. We wanted to show not only the simultaneity but also the correlation in direction between scattered quantum and recoil electron, as it must exist according to the Compton theory—this means according to the laws of elastic collision between two bodies. In this experiment the high-energy gamma radiation of a radiothorium source was used. The result again was definitely positive. Thus, not only the strict validity of the law of conservation of energy but also of the conservation of momentum was demonstrated.

The period of my work with Geiger ended unfortunately in 1925 when Geiger was called to the University of Kiel. Again, for reasons of "economy in science," we agreed that our common fields of investigation should be divided between us, and Geiger generously offered that further coincidence work, if any, should be performed in my laboratory.

The possibility of a mere statistical validity of the conservation laws, as discussed by Bohr, Kramers, and Slater, seemed important enough to justify the examination of an additional case. In the elementary processs of light *emission* a spherical wave is sent out. The question is now: Can this spherical wave give rise to an absorption process in one direction only as required by the law of conservation of energy, or is it possible for absorption processes to occur in several directions, statistically independent as expected from the theory of Bohr, Kramers, and Slater?

In such an experiment it must be kept in mind that, contrary to the Compton effect, the detection probability of an absorption process must not be much smaller than unity, since, otherwise, possibly occurring systematic coincidences would be overshadowed by the unavoidable chance coincidences. A high detection probability was achieved by choosing the source of radiation (iron or copper K fluorescent x-rays) and the gas (argon) of the two respective point counters in such a way that the absorption probability in the gas approaches unity. Obviously, it was also necessary to have the solid angles that the two point counters subtend at the source of radiation approach 2π as closely as possible. The result of this experiment (1926) indicated no systematic coincidences, at least not with a frequency expected according to Bohr, Kramers, and Slater. In this way, the strict conservation of energy in the elementary process was also assured by an experiment that gave a negative result.

The wave-corpuscle problem remained unsolved only for a short while longer. In this period, I had the good fortune to be able to discuss this problem with Einstein. Several experiments performed at Einstein's suggestion did not bring any decisively new results. The solution (at least the formal one) came later from wave mechanics: It is simply included in the assumption of the Schrödinger theory that the Schrödinger wave of a system of n particles is a wave in the $3n$ dimensional "configuration space."



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Coincidence Counting of Cosmic Radiation

A completely different field in which the coincidence method proved extremely fruitful was the "cosmic radiation," or "ultra radiation" as it was called by its discoverer, V. Hess. In the meantime, Geiger in Kiel had developed the powerful tool of the Geiger-Müller tube counter. Coincidences between unshielded tube counters produced by cosmic rays were observed by Geiger himself as well as by W. Kolhoerster, who at this time was a guest in my Berlin laboratory.

Further important information was to be expected if absorbing layers of varying thickness were placed between or (and) above the tube counters. Such experiments performed jointly with Kolhoerster in 1929 allowed us to draw the conclusion that the cosmic radiation does not consist primarily of gamma rays, as it was generally assumed until then because of its high penetrating power, but of material particles with an energy of at least 1000 Mev. Later on, such coincidence-counter arrangements were used increasingly with more and more tube counters, sometimes also combined with cloud chambers, ionization chambers, scintillation counters, and so forth.

The nature of the primary cosmic radiation as very high energy particles was confirmed later, even though the process involved proved to be far more complex than we could surmise at that time. As a simple example we may mention that B. Rossi, also for some time a guest in my P.T.R. Laboratory, later succeeded in observing the first indications of the occurrence of particle showers by means of coincidences between tube counters placed next to each other in a *horizontal* plane (Rossi curve). Even today, the possibilities of applying the coincidence method in the field of cosmic rays are by no means exhausted.

The same principle that was used in measuring cosmic radiation can also be applied in measuring ordinary beta- and gamma-ray energies. It is, therefore, possible, with the use of only two tube counters and a variable absorber between them, to determine quite simply the average gamma energy in a mixture of gamma rays and their secondary electrons (Bothe and Becker, 1930). This method can be of use also, if for some reason the usual spectrometer method utilizing magnetic deflection cannot be applied.

In the meantime, the technique of coincidence counting was improved considerably. Instead of using the cumbersome photographic recording, we turned long ago to vacuum tube circuits in conjunction with mechanical counting devices. Not only has this the advantage of greater simplicity, but in this way it is also possible to reduce the so-called "resolving time" to such an order of magnitude that very often the disturbing "chance" coincidences are of no importance. I used such an electronic circuit with a multiple-grid coincidence tube as early as 1929. Another circuit that uses tubes connected in parallel was first designed by Rossi; it offers the advantage that it can be easily enlarged to be used for more than two coincident events, and, therefore, it is predominantly used nowadays. (Recently Z. Bay and coworkers in the U.S.A. were able to reduce the coincidence resolving time to 10^{-11} second by using electron multipliers.)

Discoveries in Nuclear Reactions

Another field in which the coincidence method can be used to great advantage is the field of nuclear reactions. It was found jointly by H. Fraenz and me (1928), as well as by Pose in Halle, that, in the artificial transmutation of a nucleus (B^{10} in our case) by alpha irradiation, several discrete proton groups of different energies appear. Shortly afterward (1930), I discovered with H. Becker the gamma rays that are emitted during alpha bombardment, not only of boron, but also of other elements. These two results have a common interpretation: the new nucleus produced during this transformation is not always formed right away in its ground state but is sometimes found in an excited state. In this case, the particle emitted during the reaction has correspondingly less energy, whereas the product nucleus changes into the ground state by emitting the stored energy in the form of gamma radiation. This change usually occurs within a time too small to be measured; therefore, it occurs practically at the same time as the emission of the new particle.

It is by no means trivial to prove the simultaneity of the two events, as one might think, because it may happen that the product nucleus is *always* produced in an excited state. This can be decided by coincidence measurements. In this case, even the particle group with the highest energy would have to be followed by gamma radiation. However, this is not the case if this group corresponds to the transition to the ground state of the product nucleus. (In case of "metastable" excited states, these considerations obviously have to be modified.) Such measurements were first performed in 1935 by H. J. von Baeyer, a Heidelberg student of mine, on the transformation of boron by alpha bombardment, which has already been mentioned. In the same manner, it is possible to decide whether two or more gamma quanta are produced in the same nucleus in one nuclear reaction, therefore produced at the same time, or whether they are alternatively emitted in the transformation of different nuclei. Such questions are of importance in energy balance considerations and, therefore, in the measurement of reaction energies and nuclear masses.

Correlations in the directions of the different radiations emitted in a nuclear reaction and the angular distribution of the emitted radiation with respect to the direction of the bombarding radiation can also be determined and measured with coincidences. Experiments of this kind furnish valuable information concerning the structure of the atomic nucleus. Corresponding problems in the spontaneous transformations (natural and artificial radioactivity) can be attacked experimentally in the same way as was shown in the case of the decay of RaC (Bothe and Maier-Leibnitz in 1937).

The wide field of nuclear physics will offer in the future many possibilities for applications of the coincidence method. It can be stated without exaggeration that this method belongs to the necessary fundamental tools of the modern nuclear physicist.

Some Effects of Periodic X-radiation

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Several studies have reported the effects of x-radiation on the physiology and behavior of animals, but generally they have employed a single, large dose of radiation. The present study (*1*) was undertaken to determine progressive behavioral and physiological changes occurring when animals are given repeated mild doses of x-radiation over a long period of time.

Twenty-three monkeys of the species *Macaca mulatta* were used in this investigation and were housed in pairs insofar as this was possible. Prior to radiation they were given extensive training on various tests that had been shown through previous experimentation to differentiate reliably between normal animals and those with various types of brain damage. Following this training, 12 of the 23 animals were randomly selected for radiation.

The weights of the experimental animals a week before radiation ranged from 5.19 to 9.44 pounds, with a mean of 7.24 ± 1.42 pounds, and the control animals weighed from 5.00 to 10.17 pounds, with a mean of 7.45 ± 1.73 pounds.

Radiation was accomplished by tying the animals in an adjustable, rotating plastic chair (Fig. 1) placed so that its axis of rotation, which was approximately the same as the long axis of the animal's body, was located 1 meter from the source of the x-rays. The whole body was irradiated, with the apex of the radiation cone located at the animal's midline slightly caudal to the heart. The x-ray machine used was a Westinghouse Quadrocondex, containing an XPT tube operating at 200-kilovolt peak and 10 milliamperes. The rays were filtered through 1 millimeter of aluminum and 0.5 millimeter of copper. The tube delivered from 6.0 to 6.2 roentgens per minute at a distance of 1 meter, and prior to each radiation the output was determined by means of a Victoreen roentgen-meter, and proper exposure times were calculated. The experimental animals were given 100 roentgens every 35 days until death.

The greatest number of roentgen units absorbed by any animal before death was 1200, in contrast with the results of Eldred and Trowbridge (*2*), who found that LD_{100} for rhesus monkeys weighing 5 to 7 pounds was 800 roentgens for a single dose. These results conform to the finding of other researchers (*3*) that divided doses are not as lethally effective as a single dose. Because of the small number of animals and the occurrence of illness in the early stages of the project, no estimate of LD_{50} is justified.

Radiation significantly affected animal weights. Eight experimental and eight control animals were paired on the basis of their mean weights for the 3-month period immediately preceding radiation. Between this period and the time of death of the experimental animal of each pair, the mean weight of the control subjects increased 9.6 percent, whereas that of experimental animals decreased by 4.7 percent. This difference is significant at the .01 level of confidence. A Pearson product-moment correlation of +.41 was obtained between mean weights of the experimentals for the 3 months prior to radiation and the cumulative number of roentgens administered before death. Although it is not statistically significant for the number of animals involved, the positive direction of this correlation suggests that weight before radiation may have some relationship to radiation resistance in monkeys.

The first two experimental animals succumbed after dosages of 300 and 500 roentgens, respectively, and were found at autopsy to have pulmonary tuberculosis. The examination was discontinued when the opened chest cavity revealed this condition. The third animal, which died after receiving a total of 900 roent-

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