TAP 534- 5: The discovery of beta decay

This reading is about an important discovery made in the early days of the study of radioactivity. It involves many of the most famous nuclear scientists of the day and led to an amazingly bold prediction of the existence of a small neutral particle, eventually called the neutrino. The theory also meant that physicists had discovered a hitherto unknown force in nature – the weak force.

Radioactivity – the emission of mysterious ‘rays’ from certain rare elements – was discovered in 1896 by the French physicist Henri Becquerel. The emissions were soon classified in terms of how penetrating they were as alpha, beta and gamma rays. The alpha rays – soon found to be massive particles, helium nuclei – left a particular source with a definite kinetic energy that was a characteristic identifier of the source. In the early days it was assumed that beta rays, identified as high-speed electrons, also left the source with a characteristic energy. Indeed early experiments carried out between 1907 and 1914 seemed to confirm this assumption. But they were wrong: the detection relied on photographic techniques that were too insensitive to reveal that some beta particles from a particular source had less energy than others.

Constant energy produces a line spectrum

Early experimenters were looking for patterns in the outputs of the various radioactive elements that were being discovered. It was possible to identify elements from the spectrum of the light they gave out when heated. It should be possible to do much the same for radioactive sources using these newer emissions. What they were beginning to realise at this time was that a good emitter like radium was changing into other radioactive elements with each emission, and it would be nice to be able to identify these from the emission they gave out. To start with it had been thought that the new elements were all forms of the original source, and they were named radium B, radium C, radium D, uranium X, etc. The idea that elements could change was against all the beliefs about atoms and elements so carefully built up in the nineteenth century.

The energy of beta particles was found by making them move through a strong magnetic field before landing on a photographic plate. The slower less energetic ones were deviated more. These experiments showed that many beta emitters produced definite lines on the plate, where betas with a particular speed congregated. But the line spectra produced were ‘messy’. For some emitters it was hard to detect the betas with a discrete and definite energy against the noisy background in the exposed plates. In Berlin, Lise Meitner and Otto Hahn were two of several scientists across Europe investigating this problem. Remember that nobody realised that all these effects were due to changes in the nucleus – the nucleus had not then been discovered.

The worst of all the emitters investigated by Meitner and Hahn was named radium E, which we now know is a radioactive isotope of bismuth (^{210}Bi). In 1911 Otto Hahn (with Lise Meitner, one of the discoverers of nuclear fission – but that was yet to come) wrote to Ernest Rutherford:

RaE is the worst of all. We can only obtain a fairly broad band. We formerly thought that it was as narrow as the other bands [as found in other emitters], but that is not true. It looks as if secondary … effects had a maximum influence on rays of a medium velocity like RaE.

Hahn was thinking that there might be some secondary process inside the atom which somehow altered the energy distribution and smoothed things out, especially effective with low-energy (soft) beta rays. Then later:

The trouble with the soft rays [from RaE] is very great and we do not feel sure that we can overpass the difficulties to obtain good lines.

But even the great Rutherford at this time was not too worried, and replied:

The continuous β-ray spectrum observed for uranium X and radium E may be ultimately resolved for a number of lines.

The problem was that there were two effects happening at the same time. Electrons from beta decay do always produce a continuous spectrum – the vital fact that was to lead to so much. But several beta emitting nuclei also emit gamma rays, which like alpha particles have single definite energies. These gamma rays can then give their energy to an electron in the outer part of the atom, knocking it out of the atom so that it looks like a beta particle from the nucleus, but one with a single definite energy. It was too attractive to physicists looking for a pattern to put more emphasis on the nice line spectra than on the vague and inexplicable continuous one. And when such lines occurred they were much easier to see on the photographic plates used than was the vaguely darkened background due to the continuous spectrum. Remember also that sharp line spectra were what physicists expected to see; that was what they were used to, and what theory told them ought to happen. So they saw what they expected.

Why is a continuous energy spectrum a problem?

So what was so important about the continuous spectrum anyway? It is always annoying for a scientist or a detective to discover that the interesting clues they are looking for are in fact far less important than the messy stuff that just seems to get in the way. But as the evidence for a continuous range of energies being carried away from a radioactive source grew, the very small numbers of what were to be called 'nuclear physicists' began to get more and more worried. The decisive evidence was coming not from hard-to-read photographic plates but from the new generation of detectors using an electrical discharge produced by the ionising radiations. In April 1914 a young 23-year-old physicist called James Chadwick was given a scholarship to do research and chose to join Hans Geiger in Berlin. Using a primitive form of what was later to be called a Geiger counter Chadwick obtained clear evidence for the continuous spectrum of beta particle energies – and not just with radium E. Chadwick was to become famous in 1932 for discovering the neutron, but choosing to go to Berlin in 1914 was not one of his better ideas. He spent the war years in an internment camp.

Is the law of conservation of energy true?

This was the question raised by the continuous spectrum of beta particle energies. To avoid answering the question with a 'NO!', physicists had to postulate a completely new particle that had no charge and negligible or zero mass. It was not shown experimentally to exist until 1956, and required a new fundamental force in nature to explain it.

The problem was simple: if some beta particles leave a nucleus with less energy than others, what has happened to the 'missing' energy? It was seriously considered in the 1920s that maybe the law of conservation of energy just didn't apply to the strange world of the quantum and the relativistic equivalence of mass and energy. In 1930 the distinguished physicist Niels Bohr said in a lecture:

At the present stage of atomic theory we have no argument, either empirical or theoretical, for upholding the energy principle in β-ray disintegrations, and are even led to complications and difficulties in trying to do so.

Then the rather eccentric Austrian physicist Wolfgang Pauli came to the rescue with a very brave idea indeed. In December 1930 he wrote a letter to a meeting of physicists at Tubingen University:

Dear radioactive ladies and gentlemen,

I have come upon a desperate way out regarding … [some fairly obscure data], as well as to the continuous β-spectrum, in order to save …. The energy law. To wit, the possibility that there could exist in the nucleus electrically neutral particles, which I shall call neutrons, which have spin ½ and satisfy the exclusion principle and which are further distinct from light-quanta in that they do not move with light velocity. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any case not larger than 0.01 times the proton mass. … The continuous β-spectrum would then become understandable from the assumption that in β-decay a neutron is emitted along with the electron, in such a way that the sum of the energies of the neutron and the electron is constant.

Some theoretical calculations pointed to Pauli’s neutral particle having zero rest mass. The word neutron seemed to too big for such a tiny, if important, object. The Italian physicist Enrico Fermi started calling it the little neutral one – or neutrino. This became the accepted name when in 1932 Chadwick discovered a much larger neutral component of the nucleus that better deserved to be called the neutron.

Practical advice

This reading is designed as an extra to support the episode. It adds some personal context to the hard to accept discovery of the continuous energy spectrum associated with beta decay. It is interesting that one of the first challenges thrown up by the comparatively simple observation of a continuous beta energy spectrum should throw doubt on one of the most fundamental laws in physics, the conservation of energy.

Social and human context

The problem of the continuous beta spectrum shows how even the greatest physicists of the day were confused by what was being discovered, and found it hard to accept. When the observations were accepted they seemed to shake one of the most basic laws of physics.

External reference

This activity is taken from Advancing Physics chapter 17, 10T