1

The atom completed and a new particle

The origins of particle physics: The atom, radioactivity, and the discovery of the neutron and the positron, 1895–1933

The fundamental achievement of physical science is the atomic model of matter. That model is simplicity itself. All matter is composed of atoms, which themselves form aggregates called molecules. An atom contains a positive nucleus very much smaller than the full atom. A nucleus with atomic mass A contains Z protons and $A-Z$ neutrons. The neutral atom has, as well, Z electrons, each with a mass only 1/1836 that of a proton. The chemical properties of the atom are determined by Z; atoms with equal Z but differing A have the same chemistry and are known as isotopes.

This school-level description did not exist at all in 1895. Atoms were the creation of chemists and were still distrusted by many physicists. Electrons, protons, and neutrons were yet to be discovered. Atomic spectra were well studied, but presented a bewildering catalog of lines connected, at best, by empirical rules like the Balmer formula for the hydrogen atom. Cathode rays had been studied, but many regarded them as uncharged, electromagnetic waves. Chemists had determined the atomic weights of the known elements and Mendeleev had produced the periodic table, but the concept of atomic number had not yet been developed.

The discovery of x rays by W. C. Röntgen in 1895 began the revolution that was to produce atomic physics. Röntgen found that cathode-ray tubes generate penetrating, invisible rays that can be observed with fluorescent screens or photographic film. This discovery caused a sensation. Royalty vied for the opportunity to have their hands x-rayed, and soon x rays were put to less frivolous uses in medical diagnosis.

The next year, Henri Becquerel discovered that uranium emitted radiation that could darken photographic film. While not creating such a public stir as did x rays, within two years radioactivity had led to remarkable new results. In 1898, Marie

Curie, in collaboration with her husband, Pierre, began her monumental work, which resulted in the discovery of two new elements, polonium and radium, whose level of activity far exceeded that of uranium. This made them invaluable sources for further experiments.

A contemporaneous achievement was the demonstration by J. J. Thomson that cathode rays were composed of particles whose ratio of charge to mass was very much greater than that previously measured for ions. From his identification of electrons as a universal constituent of matter, Thomson developed his model of the atom consisting of many, perhaps thousands of electrons in a swarm with balancing positive charge. In time, however, it became clear that the number of electrons could not be so great without conflicting with data on the scattering of light by atoms.

The beginning of the new century was marked by Planck's discovery of the blackbody radiation law, which governs emission from an idealized object of a specified temperature. Having found empirically a functional form for the energy spectrum that satisfied both theoretical principles and the high-quality data that had become available, Planck persisted until he had a physical interpretation of his result: An oscillator with frequency ν has energy quantized in units of $h\nu$. In one of his three great papers of 1905, Einstein used Planck's constant, h, to explain the photoelectric effect: Electrons are emitted by illuminated metals, but the energy of the electrons depends on the frequency of the light, not its intensity. Einstein showed that this could be explained if light of frequency ν were composed of individual quanta of energy $h\nu$.

Investigations of radioactivity were pursued by others besides Becquerel and the Curies. A young New Zealander, Ernest Rutherford came to England after initiating his own research on electromagnetic waves. He was soon at the forefront of the investigations of radioactivity, identifying and naming alpha and beta radiation. At McGill University in Montreal, he and Frederick Soddy showed that radioactive decay resulted in the transmutation of elements. In 1907, Rutherford returned to England to work at Manchester, where his research team determined the structure of the atom.

Rutherford's favorite technique was bombardment with alpha particles. At McGill, Rutherford had found strong evidence that the alpha particles were doubly ionized helium atoms. At Manchester, together with Thomas Royds, he demonstrated this convincingly in 1909 by observing the helium spectrum produced in a region surrounding a radioactive source. Hans Geiger and Ernest Marsden, respectively aged 27 and 20, carried out an experiment in 1909 under Rutherford's direction in which alpha particles were observed to scatter from a thin metal foil. Much to their surprise, many of the alpha particles were scattered through substantial angles. This was impossible to reconcile with Thomson's model of the atom. In 1911, Rutherford published his analysis of the experiment showing that the atom had a small, charged nucleus.

This set the stage for the efforts of Niels Bohr. The atom of J. J. Thomson did not a priori have any particular size. The quantities of classical nonrelativistic physics did not provide dimensionful quantities from which a size could be constructed. In addition to the electron mass, m_e, there was the electron's charge squared, e^2, with dimensions mass × length^3/time^2. Bohr noted that Planck's constant had dimensions mass × length^2/time. In a somewhat ad hoc way, Bohr managed to combine m_e, e^2, and h to obtain as a radius for the hydrogen atom $a_0 = \hbar^2/(m_e e^2)$, where $\hbar = h/2\pi$, and derived the Balmer formula for the hydrogen spectrum, and the Rydberg constant which appears in it.

Despite this great achievement, the structure of atoms with higher values of Z remained obscure. In 1911, Max von Laue predicted that x rays would show diffraction characteristics when scattered from crystals. This was demonstrated in short order by Friedrich and Knipping and in 1914 Moseley was able to apply the technique to analyze x rays emitted by the full list of known elements. He found that certain discrete x-ray lines, the K lines, showed a simple behavior. Their frequencies were given by $\nu = \nu_0(n-a)^2$, where ν_0 was a fixed frequency and a was a constant near 1. Here n took on integral values, a different value for each element. Moseley immediately understood that n gave the positive charge of the nucleus. In a stroke, he had brought complete order to the table of elements. The known elements were placed in sequence and gaps identified for the missing elements.

While the atomic number was an integer, the measured atomic weights measured relative to hydrogen were sometimes close to integers and sometimes not, depending on the particular element. Soddy first coined the term isotopes to refer to chemically inseparable versions of an element with differing atomic weights. By 1913, J. J. Thomson had demonstrated the existence of neon isotopes with weights 20 and 22. The high-precision work of F. W. Aston using mass spectrometry established that each isotope had nearly integral atomic weight. The chemically observed nonintegral weights were simply due to the isotopic mixtures. It was generally assumed that the nucleus contained both protons and electrons, with their difference determining the chemical element.

The story of the years 1924–7 is well-known and needs no repeating here. Quantum mechanics developed rapidly, from de Broglie's waves through Heisenberg's matrix mechanics to its mature expression in the Schrödinger equation and Dirac's formulation of transition amplitudes. The problem of the electronic structure of the atom was reduced to a set of differential equations, approximations to which explained not just hydrogen, but all the atoms. Only the nucleus remained a mystery.

While the existence of the neutron was proposed by Rutherford as early as 1920, until its actual discovery both theorists and experimenters continued to speak of the nucleus as having A protons and $A-Z$ electrons. The development of quantum mechanics compounded the problems of this model. It was nearly impossible to confine the electron inside a space as small as a nucleus, since by the uncertainty principle this would require the electron to have very large momentum.

By 1926 it was understood that all particles were divided into two classes according to their angular momentum. The total angular momentum (spin) of a particle is always an integral or half-integral multiple of $\hbar$. Those with half-integral angular momentum (in units of $\hbar$) are called *fermions*, while those with integral angular momentum are called *bosons*. The quantum mechanical wave function of a system (e.g. an atom) must be antisymmetric under the interchange of identical fermions and symmetric under the interchange of identical bosons. Electrons, protons, and neutrons all have spin 1/2 (angular momentum $\hbar/2$) and are thus fermions. The alpha particle with spin 0 and the deuteron with spin 1 are bosons.

These fundamental facts about spin could not be reconciled with the prevailing picture of the nucleus N_7^{14}. If it contains 14 protons and 7 electrons, it should be a fermion and have half-integral spin. In fact, it was shown to have spin 1 by Ornstein and van Wyk, who studied the intensities of rotational bands in the spectrum of N_2^+, and shown to be a boson by measurements of its Raman spectrum by Rasetti. These results were consistent with each other, but not with the view that N_7^{14} contained 14 protons and 7 electrons.

Walter Bothe and Herbert Becker unknowingly observed neutrons when they used polonium as an alpha source to bombard beryllium. They produced the reaction:

$$\mathrm{He}_2^4 + \mathrm{Be}_4^9 \to \mathrm{C}_6^{12} + \mathrm{n}_0^1$$

Bothe and Becker observed neutral “penetrating radiation” that they thought was x rays. In 1931, Irène Curie and her husband, Frédéric Joliot, studied the same process and showed that the radiation was able to knock protons out of paraffin. Unfortunately, Joliot and Curie misinterpreted the phenomenon as scattering of gamma rays on protons. James Chadwick knew at once that Joliot and Curie had observed the neutral version of the proton and set out to prove it. His results were published in 1932 (**Ref. 1.1**, Ref. 1.2).

Chadwick noted that the proton ejected by the radiation had a velocity about one-tenth the speed of light. A photon capable of causing this would have an energy of about 50 MeV, an astonishingly large value since gamma rays emitted by nuclei usually have energies of just a few MeV. Furthermore, Chadwick showed that the same neutral radiation ejected nitrogen atoms with much more energy than could be explained by the hypothesis that the incident radiation consisted of photons, even if it were as energetic as 50 MeV. All these difficulties vanished if it was assumed that the incident radiation was due to a neutral partner of the proton. The problem with the statistics of the N_7^{14} nucleus was also solved. It consisted simply of seven neutrons and seven protons. It had integral spin and was thus a boson. With the discovery of the neutron, the last piece was in place: The modern atom was complete.

The neutron provided the key to understanding nuclear beta decay. In 1930, Wolfgang Pauli had postulated the existence of a light, neutral, feebly interacting particle, the neutrino (ν). Pauli did this to explain measurements demonstrating the apparent failure of energy conservation when a radioactive nucleus emitted an electron (beta ray). The unobserved energy was ascribed to the undetected neutrino. As described in Chapter 6, Enrico Fermi provided a quantitative theory based on the fundamental process $n \to pe\nu$.

In the same year as Chadwick found the final ingredient of tangible matter, C. D. Anderson began his exploration of fundamental particles that are not found ordinarily in nature. The explorations using x rays and radioactive sources were limited to energies of a few MeV. To obtain higher energy particles it was necessary to use cosmic rays. The first observations of cosmic rays were made by the Austrian, Victor Hess, who ascended by balloon with an electrometer to an altitude of 5000 m. Pioneering measurements were made by the Soviet physicist Dimitry Skobeltzyn who used a cloud chamber to observe tracks made by cosmic rays. As described in greater detail in the next chapter, charged particles passing through matter lose energy by ionizing atoms in the medium. A cloud chamber contains a supersaturated vapor that forms droplets along the trail of ionization. When properly illuminated these tracks are visible and can be photographed . The momenta of the charged particles can be measured if the cloud chamber is placed in a magnetic field, where the curvature of the track is inversely proportional to the momentum.

Anderson was studying cosmic ray particles in his cloud chamber built together with R. A. Millikan at the California Institute of Technology (**Ref. 1.3**) when he discovered the positron, a particle with the same mass as the electron but with the opposite charge. The cloud chamber had a 15 kG field. A 6-mm-plate of lead separated the upper and lower portions of the chamber. Surprisingly, the first identified positron track observed entered from below. It was possible to prove this was a positive track entering from below rather than a negative track entering from above by noting the greater curvature above the plate. The greater curvature indicated lower momentum, the result of the particle losing energy when it passed through the lead plate. Having disposed of the possibility that there were two independent tracks, Anderson concluded that he was dealing with a new positive particle with a charge less than twice that of the electron and a mass much less than that of a proton. Indeed, if the charge was assumed equal in magnitude to that of the electron, the mass had to be less than 20 times the mass of the electron.

Just a few years before, P. A. M. Dirac had presented his relativistic wave equation for electrons, which predicted the existence of particles with a charge opposite that of the electron. Originally, Dirac identified these as protons, but J. Robert Oppenheimer and others showed that the predicted particles must have the same mass as the electron and hence must be distinct from the proton. Anderson had discovered precisely the particle required by the Dirac theory, the antiparticle of the electron, the positron.

While the discovery was fortuitous, Anderson had, of course, been aware of the predictions of the Dirac theory. Oppenheimer was then splitting his time between Berkeley and Caltech, and he had discussed the possibility of there being a particle of electronic mass but opposite charge. What was missing was an understanding of the mechanism that would produce these particles. Dirac had proposed the collision of two gamma rays giving an electron and a positron. This was correct in principle, but unrealizable in the laboratory. The correct mechanism of pair production was proposed after Anderson's discovery by Blackett and Occhialini. An incident gamma ray interacts with the electromagnetic field surrounding a nucleus and an electron–positron pair is formed. This is simply the mechanism proposed by Dirac with one of the gamma rays replaced by a virtual photon from the electromagnetic field near the nucleus. In fact, Blackett and Occhialini had evidence for positrons before Anderson, but were too cautious to publish the result (Ref. 1.4).

Anderson's positron (e^+), Thomson's electron (e^-), and Einstein's photon (γ) filled all the roles called for in Dirac's relativistic theory. To calculate their interactions in processes like $e^-e^- \to e^-e^-$ (Møller scattering), $e^+e^- \to e^+e^-$ (Bhabha scattering), or $\gamma e^- \to \gamma e^-$ (Compton scattering) was a straightforward task, when considered to lowest order in the electromagnetic interaction. It was clear, however, that in the Dirac theory there must be corrections in which the electromagnetic interaction acted more than the minimal number of times. Some of these corrections could be calculated. Uehling and Serber calculated the deviation from Coulomb's law that must occur for charged particles separated by distances comparable to the Compton wavelength of the electron, $\hbar/m_e c \approx 386$ fm (1 fm = 1 fermi = 10^{-15} m). Other processes, however, proved intractable because the corrections turned out to be infinite!

In the simple version of the Dirac theory, the $n = 2$ s-wave and p-wave states (orbital angular momentum 0 and 1, respectively) of hydrogen with total angular momentum (always measured in units of $\hbar$) $J = 1/2$ are degenerate. In 1947, Lamb and Retherford demonstrated that the $2S_{1/2}$ level lay higher than the $2P_{1/2}$ level by an amount equivalent to a frequency of about 1000 MHz. An approximate calculation of the shift, which was due to the emission and reabsorption of virtual photons by the bound electron, was given by Hans Bethe.

A complete formulation of quantum electrodynamics (QED) was given by Richard Feynman and independently by Julian Schwinger, whose work paralleled that done earlier in Japan by Sin-itiro Tomonaga, The achievement of Tomonaga, Feynman, and Schwinger was to show that the infinities found in the Dirac theory did not occur in the physical quantities of the theory. When the results were written in terms of the physical couplings and masses, all the other physical quantities were finite and calculable.

A test of the new theory was the magnetic moment of the electron. In the simple Dirac theory, the magnetic moment was $\mu = e\hbar/2m_ec = 2\mu_0 J_e$, where $J_e = 1/2$ is the electron spin and $\mu_0 = e\hbar/2m_ec$ is the Bohr magneton. More generally, we can write $\mu = g_e\mu_0 J_e$. Because of quantum corrections to the Dirac theory, g_e is not precisely 2. In 1948, by studying the Zeeman splittings in indium, gallium, and sodium, Kusch found that $g_e = 2(1 + 1.19 \times 10^{-3})$, while Schwinger calculated $g_e = 2(1 + \alpha/2\pi) = 2(1 + 1.16 \times 10^{-3})$. The currently accepted experimental value is $2(1 + 1.159652209(31) \times 10^{-3})$ while the theoretical prediction is $2(1 + 1.159652478(127) \times 10^{-3})$. The brilliant successes of QED made it the standard for what a physical theory should achieve, a standard emulated three decades later in theories formulated to describe the nonelectromagnetic interactions of fundamental particles.

EXERCISES

1.1 Confirm Chadwick's statement that if the protons ejected from the hydrogen were due to a Compton-like effect, the incident gamma energy would have to be near 50 MeV and that such a gamma ray would produce recoil nitrogen nuclei with energies up to about 400 keV. What nitrogen recoil energies would be expected for the neutron hypothesis?

1.2 The neutron and proton bind to produce a deuteron of intrinsic angular momentum 1. Given that the spins of the neutron and proton are 1/2, what are the possible values of the spin, $S = S_n + S_p$ and orbital angular momentum, L, in the deuteron? There is only one bound state of a neutron and a proton. For which L is this most likely? The deuteron has an electric quadrupole moment. What does this say about the possible values of L?

1.3 A positron and an electron bind to form positronium. What is the relationship between the energy levels of positronium and those of hydrogen?

1.4 The photodisintegration of the deuteron, $\gamma d \to pn$, was observed in 1934 by Chadwick and M. Goldhaber (Ref. 1.5). They knew the mass of ordinary hydrogen to be 1.0078 amu and that of deuterium to be 2.0136 amu. They found that the 2.62 MeV gamma ray from thorium C$''$ (Th^{208}_{81}) was powerful enough to cause the disintegration, while the 1.8 MeV γ from thorium C (Bi^{212}_{83}) was not. Show that this requires the neutron mass to be between 1.0077 and 1.0086 amu.

1.5 * In quantum electrodynamics there is a symmetry called charge conjugation that turns electrons into positrons and vice versa. The "wave function"of a photon changes sign under this symmetry. Positronium with spin S (0 or 1) and angular momentum L has charge conjugation $C = (-1)^{L+S}$. Thus the state ${}^3S_1$ $(S = 1,\ L = 0)$ has $C = -1$ and the state ${}^1S_0$ $(S = 0,\ L = 0)$

has $C = +1$. The ${}^1S_0$ state decays into two photons, the ${}^3S_1$ into three photons. Using dimensional arguments, estimate crudely the lifetimes of the ${}^1S_0$ and ${}^3S_1$ states and compare with the accepted values. [For a review of both theory and experiment, see M. A. Stroscio, *Phys. Rep.*, **22**, 215 (1975).]

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