Preface to *Radioactive Transformations*

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Rutherford's *Radioactive Transformations* is, of course, a scientific document, but that is no longer its primary interest. The discoveries it announces have long since been assimilated into textbooks, and appear as special cases within much more comprehensive and coherent bodies of knowledge. Nevertheless we can read it with pleasure and profit today, as a remarkable piece of literature combining traveller's tale, historical chronicle, and accidental autobiography.

As a traveller's tale: It is a richly detailed description of a strange new world, a world distilled from ours by weird and laborious procedures the old alchemists could call their own, a world of causeless transformations and bizarre emanations.

As an historical chronicle: It recounts an epoch when "discoveries of the most striking interest and importance have followed one another in rapid succession ... The march of discovery has been so rapid that it has been difficult even for those directly engaged in the investigations to grasp at once the full significance of the facts that have been brought to life." In retrospect, it appears as the time when physics first truly came to grips with the issue of what matter *is*, as opposed to how matter, being given, behaves. It was a time of suddenly expanding horizons, awakened ambitions, and triumphal achievement.

As accidental autobiography: Rutherford speaks not a personal word, yet from the pages of *Radioactive Transformations* a remarkable, and remarkably attractive, personality emerges. He is a real-life Sherlock Holmes, fastening on odd facts, theorizing within their discipline, relentless to test his intuitions. Yet in his candor and simplicity of character, and what appears in retrospect as occasional theoretical naivete, there's also a leavening pinch of Doctor Watson.

Radioactive Transformations is based on Ernest Rutherford's Silliman Lectures for 1905. Following Thomson's discovery of the electron in 1897 and Becquerel's discovery of radioactivity, suddenly atoms were no longer the ideal objects posited by ancient philosophy and contemporary theory: indivisible, unchanging, and therefore immune to analysis. No! Atoms had parts, and they changed, spontaneously, in peculiar, seemingly whimsical ways. Lacking ultimate simplicity, atoms could – and for a man like Rutherford, that meant they *must* – be understood more deeply. They must be looked into, and taken apart, until their inner logic was revealed. The theoretical physics of the time was, manifestly, not up to the job. It was a heady time for experimental physics, perfectly suited to Rutherford's ingenuity, energy, and ambition.

The Context: An Age of Revolutions

The word "revolution" is overused in the history of science. Indeed, a primary virtue of science is that its laws are rooted in evidence, and subject to continuous scrutiny and amendment. Scientific ideas and models of long standing have been tested and strengthened over time. Therefore truly radical changes, as opposed to additions and refinements, are rare. Yet in 1905, in physics, Rutherford was creatively engaged with two genuinely revolutionary developments: intimations of the Divisibility, and of the Instability, of the basic constituents of matter.

Today atomic and nuclear physics are mature subjects, supported in dense, seamless webs of facts and ideas. They allow long chains of confident deduction, and enable complex engineering projects. In other words, they have been domesticated. But in 1905 they were wild. The first chapter of *Radioactive Transformations*, entitled "Historical Introduction", is Rutherford's take on the state of play. It is a fascinating account, not to be missed, but it is aimed toward a reader who no longer quite exists: sophisticated in the physics and experimental technology of 1905, yet innocent of many basic (later) discoveries that children learn today. So a few words of orientation and perspective may be in order here.

Divisibility: Atomic Deconstruction

Deconstruction of atoms takes place when rarefied gases are subject to strong electric fields. The process could be realized and studied conveniently within Crookes tubes – that is, glass tubes evacuated to near vacuum, with electrodes at each end. As we understand it today, a voltage difference across the electrodes creates electric fields, that will accelerate charged particles within the gas. Ionized atoms and electrons, always present at some small density due to cosmic rays or thermal excitation, get boosted to high energy. They become projectiles, capable of breaking apart other atoms. The products include new charged particles, which are accelerated in turn, in a chain reaction that makes bottled lightning.

In 1897 J. J. Thomson made an epochal discovery. As we have discussed, in a high-voltage Crookes tube the charged debris of atom-breaking collisions streams toward the electrodes. Some fast-moving positively charged ions will impact the lower-voltage electrode (the cathode). Negatively charged particles emerge from those impacts and stream toward the high-voltage electrode (the anode). Thomson studied these "cathode rays". He established that they consist of particles, each with the same quantity of electric charge and the same mass, whatever the cathode is made from. He went on to demonstrate that hot materials and radioactive materials emit particles with those same characteristics. Putting it together, Thomson deduced that there was a universal *subatomic* building-block of matter. This is, of course, what we now call the electron.

The cathode rays, as just discussed, have a simple universal character, being made of electrons. The positively charged "anode rays" are another story altogether. They are the remainders of atoms, after one or more electrons get stripped away. Those remainders (we now know) consist of the atomic nuclei, together with a variable number of electrons. Thus anode rays come in many varieties, and retain features that distinguish among different chemical substances. The pioneering work in Crookes tubes thereby posed a challenge as clear as it was grand: To continue the analysis of matter by understanding, as concretely as one understood electrons, those complementary components of atoms. Heightening the challenge: The mass of individual electrons was found to be only a tiny fraction (less than 1/1000) of the total mass of individual atoms.

Besides (and prior to) electrons, the pioneering work on high-voltage electric discharges in Crookes tubes gave subatomic science another big gift: x-rays. Röentgen is generally credited for their discovery, as his systematic experimental studies of 1895 – including a spectacular image of the bones of his wife's hand – brought the subject to an entirely new level. The possibility of high-frequency electromagnetic waves was already implicit in Maxwell's 1861 synthesis (Maxwell's equations), and on that basis the existence a new type of highly penetrating radiation was anticipated mathematically by Helmholtz. Still, Röentgen's discovery had tremendous psychological impact: Suddenly it was important and plausible to look for *weird* physical phenomena, purely experimentally. Complacent faith in the near-closure of classical physics was no longer viable.

The strangeness and vividness of actual x-rays, and their potential for medical and scientific applications, inspired a surge of experimental activity. This exploration led to major progress on several fronts including, as we discussed, the discovery of the electron. But for our story the most important result was a chance discovery by Henri Becquerel, in 1896.

Instability: Radioactivity

Becquerel was studying phosphorescence, that is the ability of certain materials to absorb high-frequency electromagnetic energy, such as the ultraviolet part of sunlight, or x-rays, and then to emit some of that energy as visible light. (Phosphorescence that ceases rapidly once the energy source is removed is called fluorescence, but I won't insist on that distinction, which is not fundamental.) Phosphorescence was, and still is, a convenient way to detect and monitor x-rays. Becquerel found, however, that the uranium salts he was studying would "phosphoresce" spontaneously and at a steady rate, without prior exposure to sunlight, x-rays, or any other energy source. Furthermore, he demonstrated that some of the spontaneous radiation from these salts is more penetrating than ordinary light, or even x-rays, being capable of passing through opaque paper or even metal sheets. Becquerel had discovered a fundamentally new behavior of matter: Radioactivity.

Nineteenth century theoretical physics was utterly unprepared for radioactivity. Caught by surprise, it had no answers to the most basic empirical questions: What materials are radioactive? What, exactly, do they emit? Answers could only come from experiment.

In celebrated, heroic chemical work Marie and Pierre Curie isolated elemental sources of radioactivity. A host of investigators, with Rutherford at the forefront, got to work analyzing the rich, complex story of exactly who decays into whom, emitting what[1].

Radioactive Substances chronicles the progress made over the first decade following Becquerel's surprise. Read in that light, the achievement is astounding. Having appropriate humility, I will venture no further here into the particularities of radioactive transformations, deferring to Rutherford's text.

Quantum Mechanics

Still less could the theoretical physics of 1905 locate the significance of radioactivity in the grand scheme of things. With hindsight, we know that theoretical understanding in this realm could not progress very far without revolutionary insights from quantum mechanics and (special) relativity – ideas that in 1905 were just aborning.

Indeed the most basic aspects of radioactivity feature characteristic *quantum mechanical* behaviors:

- The decays are spontaneous. Their rate is not affected by external conditions. Furthermore it is unpredictable which particular atomic nuclei will decay within a given interval of time;

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[1] I should note that this way of framing the issue, which now is so familiar and seems so natural that we can scarcely avoid projecting it onto the phenomena, was itself a major conceptual innovation: it is the "disintegration theory" of Rutherford and Soddy.

only the overall rate of decay, averaged over many nuclei, is fixed. Those features were already suggested in the earliest work on radioactivity, as duly emphasized by Rutherford. Cognizant of the difficulty of reconciling the apparent facts with conventional notions of causality and determinism, he raised the issue of whether some hidden subatomic structure with subtle long-term instabilities might be at work inside radioactive materials. Today most physicists have come to accept this kind of individual indeterminism within statistical predictability as a fundamental feature of the world. It is certainly a foundational principle of quantum theory.

- Ironically, the occasional spontaneous decay of atoms highlights, by way of contrast, the profound *integrity* atoms ordinarily display. As Rutherford does not fail to note, the very possibility of chemistry and spectroscopy, which rely on all atoms of the same element displaying the same intricate behaviors wherever and whenever they are observed, belies the possibility of modeling their decay as gradual erosion followed by sudden collapse and disintegration. The integrity of atoms posed an insurmountable problem for classical physics. It inspired Bohr's heretical introduction of "stationary states" in his atomic models of 1913, which initiated the quantum theory of matter.

- It was natural, as Rutherford notes, to interpret one form of radioactive emission, the γ rays, as electromagnetic pulses, i.e. part of a continuum extending light and x-rays to still higher frequency. The γ rays were often produced in associated with rapidly accelerated electrons (β rays), they were much more penetrating than the other common radiations (α and β rays), and they were not deflected by magnetic fields. All these properties are consistent with expectations for high-frequency electromagnetic waves, whose existence and properties followed from Maxwell's equations. And yet the γ rays seemed to be particles, not waves: they deposit their energy along straight paths. This situation, that equations for waves are associated with manifestations of particles, epitomizes another central, general feature of the quantum world.

These quantum features of the nuclear world leap out, as experimental facts, in radioactivity. They were not ripe for interpretation, however, in the historical development. Their context was too unfamiliar and poorly understood. As we'll discuss below, the very concept of "atomic nucleus" only emerged in 1913, and a reasonably coherent (though still crude) picture of atomic nuclei was only achieved in 1931. The rules of quantum physics were instead inferred, for the most part, from studies in more mature branches of physics, especially the thermodynamics of electromagnetic radiation (black body formula) and atomic spectroscopy (Bohr atom), and – more remotely – Hamilton's mathematical synthesis of particle mechanics and wave optics. What is remarkable, philosophically, is that the rules derived in those tame, domesticated contexts proved to apply also in the much more extreme, exotic context of nuclear (and later, subnuclear) transformations. Indeed, the most paradoxical elements of quantum theory are on display, stark and unadorned, in the simplest observations on radioactivity.

Relativity and Mass

There is a widespread misconception that Einstein's special relativity, and specifically the mass-energy relation $E = mc^2$, ushered in the nuclear age. In reality the two fields, nuclear physics and relativity, developed in parallel and almost independently. As with quantum theory, a mature understanding of special relativity theory *might have* sped the development of nuclear physics, had such mature understanding been available. But Rutherford's Silliman lectures for 1905 already report a very substantial development of experimental nuclear physics, while 1905 is also, famously, the year of Einstein's first relativity papers.

Radioactive Transformations touches on a fundamental issue that was in the air at the time, which really was close to the concerns that stimulated special relativity. That is, the question of the origin of the electron's mass, and how that mass might be affected by its motion. On page 10-11 we find

> J. J. Thomson had shown in 1887 that a charged body in motion possessed electrical mass in virtue of its motion ... The moving charge acts as an electric current, and a magnetic charge is generated round the body and moves with it. Magnetic energy is stored in the medium surrounding the charged body, which consequently behaves as if it had a greater apparent mass than when uncharged. This additional electric mass, according to the theory, should be constant for small speeds but should increase rapidly as the velocity of light is approached.
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> Kaufmann found from his experiments that the apparent mass of the electron did increase with speed, and that the increase was rapid as the velocity was rapid as the velocity of light was approached ...
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> This was very important result, for it indirectly offered a possible explanation of the origin of mass, which has always been such an enigma to science. If a charge of electricity in motion exactly simulates the properties of mechanical mass, it is possible that the mass of matter in general may be electric in origin, and may result from the movement of the electrons constituting the molecules of matter.

and on page 260

> We thus arrive at the remarkable conclusion that the particles of the cathode stream and the β particles of radium are not matter at all in the ordinary sense, but disembodied electrical charges whose motion confers on them the properties of ordinary mass.

Einstein's work gave an alternative account of the apparent increase of mass[2], or as we might say today inertia, with velocity, and established the speed of light as the limiting speed. The attractive idea that the electron's mass might be explained as field energy never proved very fruitful; indeed, modern renormalization theory discredits it. On the other hand, as we'll review below, closely related ideas really do explain, in the framework of quantum chromodynamics, most of the mass of atomic nuclei!

Only *after* mature nuclear models had been formulated could the accurate formulas of relativistic mechanics, necessarily including the possibility of converting mass into energy, and conversely energy into mass, be of serious use. Their application has been very important and fruitful, as we'll discuss momentarily.

The Legacy of *Radioactive Transformations*

So much for context and background. Allowing *Radioactive Transformations* to speak for itself, my next task is to locate its achievement in the perspective of later developments. In this part I will briefly review developments whose roots can be clearly discerned in *Radioactive Transformations*; in the following, concluding part I will sketch later developments in the subject area, that go well beyond anything Rutherford could envisage.

Mature Atomic Models

The key discovery leading to modern, successful atomic models was made by Geiger and Marsden in 1911. Working in Rutherford's laboratory and following his suggestion, Geiger and Marsden studied the deflection of α particles, emitted in radioactive decay of radium, as they impact a gold foil. They discovered that a small, but easily measurable fraction of those α particles are scattered through very large angles. Since 1907 α particles were known, again through Rutherford's

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[2] It is now standard, when speaking of the mass of a particle, to refer to its rest mass. The velocity-dependent mass that figured in the early literature (in two varieties, longitudinal and transverse) caused ambiguity and confusion, and has been abandoned. Of course the underlying empirical fact, that it becomes increasingly difficult to accelerate a particle as its speed approaches the speed of light, remains valid.

work, to be helium atoms – i.e., helium atoms lacking two electrons, which we *now* recognize as helium nuclei. The α particle have substantial inertia, so they can't be much deflected unless they encounter some stiff resistance; roughly speaking, unless they bounce from a small, very heavy object. Rutherford had not expected such large deflections to occur:

> It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you. On consideration, I realized that this scattering backward must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. It was then that I had the idea of an atom with a minute massive center, carrying a charge[3]

Rutherford proposed a definite, remarkably simple model that explains the observations. He proposed that within each atom there is a tiny nucleus, containing all of its positive charge and almost all of its mass. The remainder of the atom, according to Rutherford, consists of negatively charged electrons, in dispersed over a much larger volume. He put this model to work, and validated it, by accounting *quantitatively* for the large-angle scattering. Extrapolating the standard formulas for electrical forces, that is Coulomb's law, according to which the force is proportional to the product of charges and inversely proportional to the square of the separation, he calculated the number of α particles that will be scattered, as a beam travels through material dotted with point-like nuclei[4]. One can compare the results not only for overall rate, but for the rate as a function of the angle of deflection. Rutherford's calculated rates, based on this simple atomic model, matched the observations.

This was an epochal result. It showed that the problem of understanding the atomic structure of matter could be divided conveniently into two parts. They correspond to what we now call atomic and nuclear physics.

One part (atomic physics) is to consider a heavy, positively charged nucleus as given, and then determine how electrons are bound to it. Rutherford's explanation of the Geiger-Marsden result, based on electrical forces, also made it plausible that a known force law, namely the electric at-

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[3] Quoted in David C. Cassidy, Gerald James Holton, Gerald Holton, Floyd James Rutherford, (2002) *Understanding Physics*, Harvard Project Physics, p. 632 (BirkhŁuser).

[4] This particular experiment put an upper limit of 3.4×10^{-14} meters on the nuclear size, which is about five times what we now know the size to be.

traction of oppositely-signed charged particles, could be correctly extrapolated down to subatomic distances. It was natural to ask whether that force might be all that is required to build accurate atomic models.

That attractive idea, unfortunately, foundered on a very basic difficulty. Consider the simplest atom, hydrogen, with a single electron. According to classical mechanics and electromagnetism, as the electron orbit the nucleus it emits electromagnetic radiation, losing energy and spiraling in. There are no stable orbits.

Niels Bohr, then a young visiting scholar – the house theorist, we might say – with Rutherford in Manchester, cut through that Gordian knot in 1913. He kept the classical force law, but boldly modified the rules of mechanics. He proposed that not all orbits are allowed, but only a discrete subset of them, for which certain dynamic quantities are whole-number multiples of a universal constant, Planck's quantum[5]. Electrons can decay from higher-energy orbits into lower-energy ones, emitting electromagnetic radiation whose frequency, according to earlier ideas suggested by Planck and Einstein, should be proportional to the energy difference. In this way Bohr was able to account quantitatively for the spectral lines of hydrogen. Bohr's success validated Rutherford's basic picture of atoms, and set the agenda for a generation of theoretical physicists: to ground Bohr's *ad hoc* rules into a logically coherent mathematical theory. It was from these struggles that modern quantum theory was forged.

The other part (nuclear physics) is to understand what those inner core of atoms, are made of, and the laws that govern them. Here it becomes clear that electric forces will not suffice. Indeed the nuclei feature concentrated positive charge, which – if not overbalanced by other force – will blow apart through electric repulsion[6]. New forces, unknown to classical physics, had to be at work.

Mature Nuclear Models

Thus nuclear physics posed two challenges: the existential challenge, of identifying the ingredients of nuclei, and the dynamical challenge, of understanding the forces that those ingredients exert on one another.

The census of ingredients was settled in a few years, and rather simply. One ingredient was more or less obvious. The hydrogen nucleus is stable, (apparently) indivisible, and carries one (positive)

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[5] For experts: In Arnold Sommerfeld's crisp reformulation, the condition is that the action, integrated over an orbital period, is an integer multiple of Planck's constant.

[6] The other force from classical physics, gravity, is negligibly small in nuclear physics.

unit of electric charge. It is the lightest of all nuclei, and other light nuclei have masses that are close to whole-number multiples of its mass. So this *proton* – named by Rutherford – was one ingredient. The most economical assumption was that this is the only new ingredient! Perhaps nuclei consist, like the atoms of which they are the core, of protons and electrons bound together, with powerful new short-range forces enabling much tighter binding.

In 1920 Rutherford proposed a refinement of that idea. Both the proposal and the reasoning behind it proved prescient:

> Under some conditions, however, it may be possible for an electron to combine much more closely with the H nucleus, forming a kind of neutral doublet. Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope, and it may be impossible to contain it in a sealed vessel. On the other hand, it should enter readily the structure of atoms, and may either unite with the nucleus or be disintegrated by its intense field.
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> The existence of such atoms seems almost necessary to explain the building up of the nuclei of heavy elements; for unless we suppose the production of charged particles of very high velocities it is difficult to see how any positively charged particle can reach the nucleus of a heavy atom against its intense repulsive field.

The properties Rutherford imputes to his "neutral doublet" are very close indeed to the properties of the neutron, discovered by James Chadwick in 1931[7]. He was led to his idea by the problem of understanding how, by physical means, heavy nuclei could ever have been assembled. The difficulty is that powerful electric repulsion acts between nuclei, and makes them difficult to bring together. Even if new attractive forces come into play at short distances, and are capable of fusing the nuclei once they are brought together, first that repulsive barrier must be overcome. Rutherford envisaged a clever way around the problem: His neutral doublets would feel no repulsion, and so they might form a delivery system to sneak additional protons (together with tightly bound electrons) into nuclei. Once inside the electrons might be stripped from the doublets and expelled, to make β radiation. As we'll soon discuss, this way of building up heavy nuclei is essentially what occurs in supernova explosions, and also in nuclear reactors and bombs.

On the other hand there was never any evidence for the sort of powerful new forces between

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[7] Chadwick quoted the above passage in his 1935 lecture accepting the Nobel prize for his discovery of the neutron.

electrons and protons that Rutherford's "neutral doublet" required. In nuclear physics the neutron stands on its own, an independent ingredient as fundamental as the proton[8].

The experimental discovery of the neutron, an electrically neutral particle only slightly heavier than a proton, was a big advance, because it allowed a simple yet useful picture of what nuclei are, namely that nuclei are collections of protons and neutrons, bound together. With that picture, many observed facts fell into place:

- *Atomic number* The nuclei of different elements differ in the number of protons they contain. That number determines the electric charge of the nucleus, which in turn controls its interaction with the surrounding electrons in an atom. Those surrounding electrons, in turn, control the atom's chemical properties.
- *Isotopes* One may have several kinds of nuclei each with the same number of protons, but different numbers of neutrons. Such nuclei are called isotopes. Atoms containing isotopic nuclei will have the same chemical properties, but differ in weight. They also differ in stability; for example, different isotopes of uranium exhibit drastically different levels of radioactivity.
- *Mass Defects* The total mass of a nucleus is approximately – but only approximately – equal to the sum of masses of the protons and neutrons that make it up. This is a most profound fact, that marked the emergence of mature nuclear physics. It has two aspects, depending on where the emphasis is put.

  Because the basic idea is profound, beautiful, and nicely captured in three simple equations, I'll use up my quota of equations, which happens to be three, here. For Z protons and N neutrons we have the total mass and rest-energy

  $$\begin{aligned} M_{\text{constituents}} &= Z m_{\text{proton}} + N m_{\text{neutron}} \\ E_{\text{constituents}} &= (Z m_{\text{proton}} + N m_{\text{neutron}}) c^2 \end{aligned} \tag{1}$$

  In the nucleus there is additional energy associated with the interactions, so we have

  $$E_{\text{nucleus}} = (Z m_{\text{proton}} + N m_{\text{neutron}}) c^2 + E_{\text{interactions}} \tag{2}$$

  Dividing by c^2, we have for the mass of the nucleus

  $$M_{\text{nucleus}} = (Z m_{\text{proton}} + N m_{\text{neutron}}) + E_{\text{interactions}}/c^2 = M_{\text{constituents}} + E_{\text{interactions}}/c^2 \tag{3}$$

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[8] Today we know that both protons and neutrons are made from quarks and gluons, according to very similar body plans.

> Thus the difference between the measured mass of a nucleus and the total mass of its constituents, which are both measurable quantities, is $E_{\text{interactions}}/c^2$. It is known as the mass defect of the nucleus. (For experts: Since the interactions are primarily attractive, $E_{\text{interactions}}/c^2$ is negative.)
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> The fact that the mass defect is much smaller than the naive "constituent counting" mass – it never reaches more than 5%, for any nucleus – shows that the interactions of protons and neutrons within nuclei, though powerful, are not so strong as to challenge their integrity as mass-units. In this quantitive sense, the nucleus *is* a collection of definite numbers of protons and neutrons.

Nuclear Transformations

At first the variety of transformations seemed bewildering – *Radioactive Transformations* testifies to that! The naturally occurring, spontaneous processes of radioactivity initiated the subject. Additional transformations were observed to result from impacts of energetic radioactive emissions, especially α particles, on target foils. Clarity as to the constitution of nuclei, as just described, also brought order into the description of their transformations.

One kind of transformation involves changes in the disposition of protons and neutrons, without any change in their numbers. An example is the original nuclear reaction

$$^{14}\mathrm{N} + \alpha \;\rightarrow\; ^{17}\mathrm{O} + p \tag{4}$$

studied by Rutherford in 1917. Here the superscripts indicate the total number of protons plus neutrons in the nucleus. He observed that upon bombarding nitrogen with α particles one sometimes observed oxygen nuclei and protons as products. Counting up the protons and neutrons: On the left-hand side we have seven protons and seven neutrons in $^{14}\mathrm{N}$ and two protons and two neutrons in the α particle; on the right-hand side we have eight protons and nine neutrons in $^{17}\mathrm{O}$, and an additional proton. So on each side we have nine protons and nine neutrons. In the reaction these particles have been rearranged, but neither created nor destroyed.

Most radioactive decays involving α emission are of this kind. The parent nucleus turns into a different nucleus, that has two protons and two neutrons fewer.

In the other kind of transformation, neutrons convert into protons (or *vice versa*). The prototype of this kind of transformation is the decay of a free neutron into a proton, an electron, and an antineutrino:

$$n \;\rightarrow\; p + e + \bar{\nu} \tag{5}$$

When it occurs inside a nucleus, this transformation leads to emission of an electron, or β ray. Proper discussion of the antineutrino would involve us in a long digression; suffice it to say that it is a neutral particle whose interactions with matter are very feeble, so that it was not detected at all in the early experiments.

The reverse conversion

$$p \;\rightarrow\; n + \bar{e} + \nu \tag{6}$$

is not very important in radioactivity, but it is the central process powering stars[9]. Here $\bar{e}$ is an antielectron (positron), and ν is a neutrino. Conversion of protons into neutrons cannot happen for isolated protons, since the neutron is heavier, but it can and does happen in nuclear environments, where more favorable interaction energy for the neutron can compensate for its unfavorable rest-energy.

Decays involving conversions between neutrons and protons are invariably slow, and reactions involving such conversions are invariably rare.

All the observed transformations of nuclei, including the many processes recorded in *Radioactive Transformations*, are of these two basic kinds: rearrangements of protons and neutrons, or single neutron↔proton conversions. The latter are accompanied by emission of electrons, neutrinos, or their antiparticles.

Applications

- *Stellar Nucleosynthesis*

  Nuclear transformations provide the primary source of energy for stars, including our Sun. In normal ("main sequence") stars the dominant process is fusion of hydrogen into helium. It proceeds through a number of intermediate steps, including two $p \rightarrow n$ conversions. The net result is

  $$4\,{}^1\mathrm{H}\;(= 4p) \rightarrow {}^4\,\mathrm{He}\;(= \alpha) + 2\bar{e} + 2\nu \tag{8}$$

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[9] There are a few examples of nuclei that decay through the interesting process of electron capture, following the schema

$$p + e \;\rightarrow\; n + \nu \tag{7}$$

In this process, the nucleus "captures" one of the surrounding electrons from its atomic cloud

The hydrogen nucleus ^{1}H is the proton p, and the helium nucleus ^{4}He, as mentioned previously, is none other than the α particle, . ^{4}He contains two protons and two neutrons. It is a particularly stable nucleus, with a large mass defect. Due to that mass defect, the reaction (8) liberates energy. This is the energy that powers our Sun.

It is very important that the stellar fusion of hydrogen into helium requires two $p \rightarrow n$ conversions, which are rare events. That is why stars can stay alight for billions of years, supporting a slow but steady burn.

When a star runs out of hydrogen fuel, it starts to contract, raising its temperature. Eventually the temperature rises so high that helium nuclei fuse. (That process requires a higher temperature than hydrogen fusion, in order to overcome the stronger barrier of electric repulsion facing the more highly charged helium nuclei.) The dominant fusion, $3^4\mathrm{He} \rightarrow^{12} \mathrm{C}$, involves only rearrangement of protons and neutrons, not an conversion, so it occurs relatively rapidly.

As helium is exhausted there can be additional rounds of fusion at still higher temperatures, but eventually the star exhausts its fuel. What happens at that point depends primarily on the size of the star. Stars like our Sun settle down into white dwarfs. But the collapse of significantly more massive stars is catastrophic. The gravitational energy unleashed by the collapse heats the infalling matter to extraordinarily high temperatures, causing it to explode as a supernova. (This is a rough sketch of one class of supernovae, the so-called type II supernovae. Type I supernovae arise when matter from a companion star accretes onto a white dwarf, until the bloated dwarf collapses under its own weight.)

Supernova explosions populate the interstellar medium with heavy nuclei. Some of these (for example, ^{12}C nuclei are simply the ashes of earlier fusions); others, including all those heavier than iron, are produced in the explosion itself. The path to these heavier nuclei is basically the one that Rutherford conceived in 1920: The exploding matter contains many free neutrons which, facing no barrier from electrical repulsion, readily enter and accumulate on ambient nuclei, allowing them to grow.

There is a richly detailed theory of the astrophysical processes that produce nuclei, starting from a mixture of hydrogen and helium[10]. It gives an excellent account of the relative abundances of nuclei as observed in Nature. Thus we have, based fundamental nuclear physics and astrophysics, a validated quantitative explanation of the origin of the chemical elements, and also of their isotopes.

- *The Origin of Radioactivity*

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[10] A few of the lightest nuclei were primarily produced in big bang. See below.

If radioactivity is a process of decay, leading from active (unstable) nuclei to inert products, how – or why – did it ever begin? The theory of stellar nucleosynthesis, with the final liberation of synthesized heavy elements in supernova explosions, provides a poetic, historically resonant explanation of radioactivity's origin.

In the violent last throes of its disintegration, as a star explodes, vast quantities of energy is pumped into the escaping matter. In that environment barriers that normally separate different nuclei, or nuclei and neutrons, are readily overcome, and they fuse. As these supercharged, unstable fusions settle down, some of their energy gets hung up, locked into forms that can leak out only very slowly. This is the song of phosphorescence, transposed from atomic into nuclear keys. Radioactivity is the phosphorescence of stardust.

- *Big Bang Nucleosynthesis*

  In the framework of big bang cosmology, it is possible to carry the analysis of nuclear origins back to the beginning.

  In the earliest moments of the big bang, all the material of the universe was at such high temperature, and so dense, that no complex nuclei could persist. Violent impacts with surrounding matter shattered any incipient nuclei back into protons and neutrons. But as the universe expanded and cooled, some more complex nuclei were created.

  The early cosmological environment was quite different from conditions in stars. The density was lower, but the temperatures, at least initially, were higher. The mixture was more neutron-rich, but the time available for reactions, before the expanding medium became too tenuous, was more limited.

  It is straightforward to work out the consequences of big bang nuclear synthesis. The predicted result is mostly ^{1}H, but also a substantial fraction of ^{4}He, significant ^{2}H (deuterium) and ^{3}He, and a trace of ^{7}Li[11]. The observed abundances of these nuclei are in accord with the predictions.

  Averaged over the universe as a whole, the dominant nuclei are ^{1}H and ^{4}He, reflecting big bang residues; with the above-noted exceptions, other nuclear species are products of stellar burning and supernova explosions[12].

- *Radioactivity and Chronology*

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[11] The predicted ^{7}Li abundance is small indeed, but because this nucleus is even harder to produce in stellar environments, the big bang contribution must – and does – account for the observed abundance.

[12] Actually there is one more complication: A few rare nuclei arise as byproducts of cosmic ray spallation, that is as fragments of heavy nuclei impacted by energetic cosmic ray protons.

In the nineteenth century there was a great scientific controversy about the age of the Earth. Physical arguments seemed to point to a relatively modest age, around 20 million years, that seemed inadequate to geologists and evolutionary biologists.

The two main physical arguments concerned the heat of the Sun and the Earth.

One can calculate the rate at which the Sun is presently radiating energy. To account for that energy, Kelvin proposed that energy from the accretion of the Solar material might could be accumulated and gradually released. This would suffice for a few tens of millions of years. He also examined other possibilities, but found none more promising.

As we've already discussed, the Sun has another energy source, unknown to Kelvin: nuclear fusion. It can comfortably support several billion years of stable radiation.

Mining reveals that the temperature of Earth is higher in its interior. Thus the Earth is radiating internal heat. Where does the energy come from? Again, the most promising suggestion seemed to be that the gravitational energy of formation was gradually leaking away. This process, Kelvin estimated, would support the present rate of cooling after a few tens of millions of years – suggestively close to the calculated Solar age. Rutherford reviews this issue on pages 213-217 of *Radioactive Transformations*, where he emphasizes that radioactive decays supply a possible additional source of heating. Today we know that he was on the right track, although in 1905 he could not be specific as to details. Earth is heated by radioactive decays in its interior, especially decays of potassium 40 (^{40}K). This accounts for the high temperatures underground, and provides the energy the drives plate tectonics.

Besides resolving these controversies of principle, radioactivity furnishes a powerful constructive tool for dating materials. Here the pioneering work was Rutherford's 1905 estimate of the age of the Earth, or more precisely of ancient minerals, described on pages 187-191 of *Radioactive Transformations*. The methodology there described launched a fruitful, wide-ranging field of science.

- *Nuclear Technology*

  Scientific understanding of the principles of nuclear transformations have enabled new technologies.

  Most awesome, both in present achievement and future potential, is the access nuclear processes offer to energy, on scales that dwarf conventional chemical processes. The power of nuclear weapons is all too familiar. Nuclear reactors will become attractive power generators, free of carbon emissions, if issues surrounding disposal of their (quite different!) waste products can be convincingly addressed. Controlled fusion has been an alluring dream

> for decades. Many technical difficulties have been overcome, and controlled fusion itself is now routine, though large-scale energy production at economically competitive rates remains futuristic. Progress in these areas could have very large leverage indeed; one can easily fantasize world-historic innovations.
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> Quite a different nuclear technology, that has made a large and unambiguously positive contribution to human welfare, is nuclear medicine. This has many facets, but I'll mention just one here, for its historical resonance. By attaching radioactive nuclei to biologically active materials, one can deliver those nuclei to places of interest in a human body. For example, one can attach radioactive nuclei to substances readily taken up by cancer cells. Then when the radioactive nuclei decay, they reveal where the cancer is. In this way we can now take photographs "from the inside out", as x-rays enabled us to take them "from the outside in".

The mature nuclear physics we have just described, to which Rutherford contributed so decisively, is evidently a superb scientific achievement, with wide-ranging ramifications. It provides a rough but serviceable picture of atomic nuclei, that can be used to organize a wealth of data and enable impressive applications in astrophysics, cosmology, and technology.

Radioactivity in Post-Nuclear Physics

Yet to physicists semi-empirical nuclear physics remained, manifestly, an unfinished product. It achieved its successes by codifying a wealth of experimental facts in simple semi-empirical models, finessing ignorance about the fundamental forces.

The Hadronic World

The experimental study of nuclear forces soon led in unanticipated directions. The main method of investigation was the scattering experiment. Though details of implementation and interpretation are often difficult and complicated – one is dealing with *very* small and unfamiliar objects, after all – the basic concept of scattering experiments is straightforward. It is, in fact, the same concept that guided the historic Geiger-Marsden experiment, discussed previously.

To investigate, say, the force between protons, one can shoot beams of protons at other protons (i.e., a hydrogen target) and investigate their deflection. Then from the rates at which deflections through different angles occur, one can try to infer the underlying force. One can use beams of protons with different energy, and with the protons spinning in different directions, to enrich the analysis.

Experiments of this kind soon revealed that the forces between protons and neutrons do not obey any simple equation. They depend not only on distance, but also on velocity and spin, in complicated ways.

More profoundly, scattering experiments soon undermined the notion that protons and neutrons are simple particles, or that any sort of traditional "force" between them could do justice to the reality of nuclear physics. For when high-energy protons impact other protons, the typical result is not merely a deflection, but the production of new particles.

In fact a whole world of new particles was discovered in this way: $\pi, \rho, K, \eta, \rho, \omega, K^*$ and ϕ mesons and $\Lambda, \Sigma, \Xi, \Delta, \Omega, \Sigma^*, \Xi^*$ and Ω baryons being among the lightest and most accessible. The details are fascinating to experts, but only a few broad features will concern us here.

Protons and neutrons are the prototype of baryons, and all baryons share several properties. They all feel strong short-range forces in one another's presence, or in the presence of mesons, and (for experts) they are all fermions.

The most profound feature of baryons is their conservation law. Previously, we saw that nuclear transformations include processes where neutrons convert into protons, or *vice versa*. But the total number of protons + neutrons remains the same, or (we say) is conserved, despite such transformations. In the processes observed at higher energies, protons can convert into other baryons, not only neutrons. Yet the total number of baryons of all types is conserved in all processes[13].

Mesons also share common properties. They all feel strong short-range forces in one another's presence, or in the presence of baryons, and (for experts) they are all bosons. There is not a conservation law for mesons.

Very roughly speaking, we can say that baryons resemble the traditional notion of material particles, while mesons can be considered force-mediating particles, or field-quanta, analogous to photons. (But the photon itself is not a meson, because it does not exhibit the strong short-range interactions characteristic of mesons.)

Mesons and baryons, collectively, are known as *hadrons*. Aside from the proton and neutron,

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[13] Although no violation of the law of baryon number conservation has ever been detected experimentally, there are good reasons to suspect that it is not strictly exact. See the concluding section, below.

hadrons are all highly unstable particles, that decay in a small fraction of a second. Nevertheless they exist, and they can be observed and studied in considerable detail.

Thus a major suggestion from post-nuclear physics is that protons and neutrons are not fundamental particles, but just two members among a much larger family of closely related particles, the hadrons. The complexity of proton-proton forces conveys the same suggestion. The complexity of proton-electron and proton-photon forces, revealed in parallel high-energy studies, is even more convincing: Because electrons and photons *are* simple elementary particles, whose fundamental interactions are known reliably[14], the complexity of their interactions with protons must be ascribed to complex structure within the protons.

Quantum Chromodynamics

The quark model was a major step in organizing the theory of the hadronic world. It provides a picture of hadrons analogous, in its explanatory power, to Bohr's model of atoms – that is, correct in spirit and historically important, but logically incomplete and only semi-mathematical.

According to the quark model, baryons are bound states of three more fundamental entities: quarks. Quarks come in six "flavors": up u, down d, strange s, charm c, bottom b, and top t. Of these only u and d quarks appear in protons and neutrons, while only u, d and s appear in the low-mass baryons and mesons enumerated above (and many others); the heavy and highly unstable c, b, and t quarks are relatively recent additions.

How do three kinds of quarks generate hundreds of different baryons? The point is that a given trio of quarks, say u, u, d, can exist in many discretely different states of motion (analogous to Bohr's quantized orbits for electrons). These different states will have different energies, and therefore – using $m = E/c^2$ – different masses. Thus they appear, operationally, as different particles! In this way, we find that there many different particles that all correspond to the same underlying material structure, captured in different states of internal motion.

Similarly, the quark model postulates that mesons are bound states of a quark and an antiquark. A given quark-antiquark pair, say $u\bar{d}$, in various states of motion, generates many different mesons.

The quark model gives a plausible explanation for the complexity of hadronic forces, as well. Even if quarks have simple interactions, bound states containing three quarks, or a quark and

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[14] The interactions of photons and electrons among themselves, and with nuclei at low energies, can be accurately described using simple, elegant equations.

an antiquark, offer many opportunities for cross-talk and cancellations. Indeed, it is for reasons like this that chemistry (i. e., interactions of atoms) is extremely complicated even though the underlying forces between individual electrons are extremely simple.

The quark model as such, however, neither relied upon nor provided a specific theory of the forces among quarks. Maxwell's equations for electrodynamics, Newton's and then Einstein's equations for gravity, and Schrödinger's and then Dirac's equations for atomic physics set standards for beauty and accuracy that the equations of post-nuclear physics, for several decades, could not approach.

The decisive breakthrough came in 1973, with the discovery of asymptotic freedom by David Gross and myself, and independently David Politzer, and the formulation of quantum chromodynamics (QCD) by Gross and me. A proper description of that work would necessarily distort the balance of this Preface, since it brings in several difficult new concepts, so I'll happily refer you to my Nobel lecture[15]. Here I'll only describe, in a general way, four major consequences that tie in with our present themes.

- Quantum chromodynamics provides the sought-for beautiful, accurate equations governing the strong force. The structure of the QCD equations is similar to the structure of Maxwell's equations, but they are both more complex and more symmetrical[16]. (Metaphorically speaking, the equations of QCD are to Maxwell's equations as an icosahedron is to a triangle.)

  The equations of QCD provide the foundation for nuclear physics, in principle, but that application is two steps removed from the simple basics. First the forces among quarks and gluons bind them into protons and neutrons; then – as our discussion of the quark model suggested – complicated multi-particle interactions come into play when protons and neutrons influence one another. There has been remarkable progress, involving heavy use of supercomputers, in computing the structure of protons and neutrons from the equations of QCD, but accurate calculation of nuclear forces still lies in the future.

- A major consequence of QCD is that there should exist, in addition to quarks, eight color gluons. These gluons play the same role in QCD as the photon plays in quantum electrodynamics (also known as QED).

- Although QCD predicts that quarks and gluons cannot exist as isolated particles, but are

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[15] *Asymptotic Freedom: From Paradox to Paradigm*, in Les Prix Nobel 2004 (Almqvist & Wiesell International, Stockholm, Sweden) 100-124.

[16] C. N. Yang and R. Mills discovered the mathematical possibility of generalizing Maxwell's equations to embody larger symmetry, in 1956.

always “confined” within bound states such as baryons and mesons, nevertheless they are experimentally observable, in quite a direct way. In very high energy processes, one observes the emission of *jets*. Jets consist of several hadrons, all moving rapidly in the same direction. According to QCD, jets are the residue from the emission of a quark, antiquark, or gluon, observed after the original quark (or antiquark or gluon) has radiated additional gluons and quark-antiquark pairs, which self-organize into hadrons. The total energy and momentum of the jet reflects the energy and momentum of the quark (or antiquark or gluon) that triggered its formation, since energy and momentum are conserved. Thus by measuring jets one can reconstruct quarks, antiquarks, and gluons, and compare their properties with those predicted by the equations of QCD. This is a much more direct and easier use of the equations than calculating nuclear forces, and has allowed the theory to be tested quantitively in great detail.

- Quantum chromodynamics gives a compelling account of the origin of most of the mass of protons and neutrons.

  In QCD the proton is rather a more complex object that envisaged in the quark model. In addition to the trio uud of quarks that the quark model posited, protons contain additional quark-antiquark pairs and multitudes of gluons, coming to be and passing away in a dynamic equilibrium. But the crucial point is that the particles that make up a proton[17] – u and d quarks, their antiquarks, and gluons, are particles whose mass is quite small, compared to the mass of the proton they build up.

  So where does the proton’s mass come from, if not from the mass of its constituents? There is energy associated with the internal motion of the quarks and gluons, even when the proton as a whole is at rest. Let us call that energy E. That energy is concentrated in a small region of space, and seen from afar it looks like a particle (namely, a proton). According to special relativity, the localized energy E has the inertia of a mass $m = E/c^2$. And that is the origin of the proton’s mass!

  This account of the proton’s mass, from QCD, is reminiscent of early ideas about the origin of the electron’s mass from its electromagnetic field energy, which we discussed earlier, but it has the virtues of being precisely formulated and provably correct. For supercomputer calculations, working directly from the equations of QCD, give accurate quantitative results for the masses of hadrons, notably including protons and neutrons.

  Another way of stating the result, in a language we used earlier: The mass of the proton is (almost) *entirely* its mass defect!

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[17] There is also a small admixture of $s\bar{s}$ pairs, not important for this discussion.

Radioactivity in the Standard Model

Quantum chromodynamics governs the basic dynamics that builds protons, neutrons, and the other hadrons out of quarks and gluons, and the forces that bind together nuclei – the so-called strong force. Quantum electrodynamics, including notably the electric repulsion between protons, modulates that dynamics.

Neither of those two great theories, however, incorporates processes whereby protons and neutrons interconvert. Such processes are associated with much weaker forces – that's why proton↔neutron interconversion is slow (for decays) and rare (for reactions) – but since they bring in essentially new possibilities, they are both qualitatively important and readily detected. Indeed, they are responsible for many forms of radioactivity and they play a crucial role in stellar energy generation, as we've discussed.

To account for those rare conversion phenomena, physicists were led to postulate a fourth force, in addition to gravity, electromagnetism, and the strong force. This new addition, which completes our current picture of physics – the Standard Model – is called the weak force.

Post-nuclear explorations in basic particle physics, based on observations of cosmic rays and work at accelerators, revealed that the "weak" force is not just a curious anomaly, but rather a cluster of universal phenomena, encompassing a host of transformations and interactions. As with QCD, a proper description of the weak force would distort this Preface, so I'll confine myself to four brief comments on results that are relevant to my earlier themes, or lead into my upcoming conclusion

- At a fundamental level, the weak force isn't all that weak. In experiments that explore ultrahigh energies, or (equivalently) that probe interactions at subnuclear distances, smaller than 10^{-16} centimeters, the weak interaction is seen to act more powerfully than electromagnetism.
- The equations governing the weak force are strikingly similar, in their mathematical form, to the equations resemble of QCD, which in turn are generalizations of the equations of QED, namely Maxwell's equations.
- Since protons and neutrons are, as we've discussed, complex composites of simpler, more basic quarks and gluons, we should track proton↔neutron conversions to their more basic source. The deep structures underlying the conversions (6, 7) are the quark processes

$$u \quad \rightarrow \quad d + \bar{e} + \nu \tag{9}$$

$$d \quad \rightarrow \quad u + e + \bar{\nu} \tag{10}$$

Since the neutron differs from the proton by substitution of a d quark for a u quark, (9) induces (6) and (10) induces (7).

- Although it mediates conversions of one kind of quark into another, the weak force, like the strong and electromagnetic forces, and gravity, conserves the total number of quarks. This states the refinement, to the quark level, of the law of baryon number conservation[18].

Another Radioactivity?

Since the strong, electromagnetic, and weak forces are governed by equations with very similar mathematical structures, it is natural to speculate that they are merely different aspects of a single more general force. This is a concrete, modern form of the quest for a unified field theory.

This sort of speculation can be carried quite far. It can explain regularities in the patterns of particle interactions that the Standard Model ascribes to coincidence. Most impressively, it accounts quantitatively for the differences in strengths among the strong, weak, and electromagnetic interactions. Again, a proper description of these developments would lead us far afield, but one observation will serve as an appropriate conclusion to this Preface.

The unified theories necessarily include a wider class of transformations than occur in the separate parts of the Standard Model. Upon putting quarks, electrons, neutrinos and their antiparticles on an equal footing, for example, we are led as a generalization of (9) to introduce the process

$$u \rightarrow \bar{u} + \bar{d} + \bar{e} \tag{11}$$

whereby an up quark converts into up and down antiquarks, and an antielectron (= positron).

This process (11) introduces a qualitatively new effect, that is not present in the Standard Model: It violates the law of conservation of quarks, and the closely associated law of baryon number conservation. At the level of protons (and, therefore, nuclei), it leads to the possibility that protons can decay, into π mesons and positrons:

$$p \rightarrow \pi^0 + \bar{e} \tag{12}$$

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[18] Subtle effects in the weak interaction, and possibly in gravity, lead to violations of quark number conservation. Those effects are absurdly small and unobservable today, but may have been significant in the earliest moments of the big bang.

This would undercut the long-term stability of all familiar forms of ordinary matter.

Decays based on the process (12) would represent a new form of radioactivity. Inspired by modern unified field theories, experimentalists have gone to great lengths searching for it. So far the result has been negative, and therefore the rate of such decays must be quite small. The unified theories suggest rates that are not far beyond current limits. The search continues.

With his preternatural instinct for Nature's dispositions, Rutherford pointed toward such possibilities in the final paragraph of *Radioactive Transformations*.