Rutherford’s Atom

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A year and a half after he had published his celebrated paper on the nuclear model, Rutherford was busy planning an international meeting on atomic and molecular structure. This meeting, which took place in Brussels in 1913, was the second Solvay Council of Physics. As Richard Staley reminded us this morning, the first such council, whose centennial will be celebrated this October, brought together Europe’s leading physicists to discuss radiation and quanta. Their deliberations gave an important push to investigations of the use and meaning of quantization in physical theory, and, as Staley observed, can serve as a demarcator between classical and modern physics.

1. Rutherford’s atom

Rutherford had a collaborator in organizing the meeting on atomic and molecular structure. This was Marie Curie. She did not think that much would come of their efforts. “Unfortunately [she wrote] we really know very little about the structure of matter and I doubt whether we will be much further advanced a year from now.” Apparently Mme Curie, although a leader of modern physics and the winner of two Nobel prizes, did not realize that her correspondent had revolutionized atomic physics the year before.

She was by no means the only knowledgeable person who missed the significance of Rutherford’s nuclear model. No notice of it appeared in *Nature*, *Revue scientifique, Physikalische Zeitschrift,* or the proceedings of the Deutsche Naturforscherversammlung in any of the years 1911-13. J.J. Thomson did not mention it in the series of lectures on the structure of the atom he gave at the Royal Institution in 1913, nor did any of the distinguished atomic physicists whose popular lectures were published in 1912 under the promising title *Les idées modernes sur la constitution de la matière*.

There were two good reasons for ignoring the nuclear atom as late as 1913. For one, its generic form, the Saturnian model, in which rings of electrons circulate around a neutralizing positive center, had been discussed and discarded several years before Rutherford resurrected it. Its first proponents had tried to trace spectral lines to oscillations of the electrons around their equilibrium rings. Calculation showed, however, that the oscillations in the plane of the rings included unstable modes that would rip the atom apart. Because of this radical *mechanical* instability, the model did not support calculations and ended in the trash with other unusable bright ideas.

Rutherford could return safely to a Saturnian model because the mechanical instability of the electronic structure played no part in his treatment of it. That is because electrons do not figure at all in his analysis of large-angle scattering of alpha particles from thin metal foils. The percentage of the incident particles reflected from the target, as measured by Hans Geiger and Ernest Marsden, could not be accounted for plausibly by an accumulation of little shoves given the particles by the atomic electrons they passed. Rather, Rutherford realized, they had to ricochet from a single close encounter with a center much more strongly charged than an electron.

Rutherford modeled a collision between an alpha particle and an atom as an encounter between two massive point charges. Since at the time most physicists pictured the alpha particle as a structure of atomic dimensions, Rutherford's assimilation of it to a point was in itself a great innovation. It presupposed the nuclear model for helium. The great potential of the model as a general representation of atomic processes lay just there, in Rutherford's tacit assumption that the alpha particle was the nucleus, or point remainder, of a helium atom stripped of its electrons.

The second reason for not including the nuclear model among useful ideas about the intimate structure of matter in 1913 was that it made no immediate connections with the then standard subjects of atomic physics: radiation, radioactivity, chemical combination, and the periodicity of the chemical elements.

Rutherford liked to say that the ricocheting of alpha particles that inspired and underpinned his model surprised him as much as the sight of artillery shells rebounding from tissue paper would have done. He had every reason to be surprised. He thought he knew all about alpha particles. It was he who first identified them among the rays from radioactive substances, who first demonstrated their particulate character by bending their paths in a magnetic field, and who first determined their relationship to helium. He pictured them as big and robust, like himself, and as unlikely to be knocked off course by flimsy electrons as he was to be influenced by chemists.

And, of course, the analogy between particle rays and artillery shells came only too readily to mind a hundred years ago. Outside the atom and the laboratory, the world was rushing toward war. That year, 1911, the revolution that ousted the Manchu dynasty broke out in China; the Italians opened war against the Turks in a precocious use of attack aircraft; Churchill became the First Lord of the Admiralty; and the Kaiser asserted Germany's "place in the sun." Three years later Rutherford and the group of able men of various nationalities around him who connected his model to wider problems in atomic physics were at war. They included, besides Geiger and Marsden, Niels Bohr, Charles Darwin, Hans Geiger, Georg von Hevesey, and Henry Moseley. Two were to fight, and one to die, for England, and two to fight for the Central Powers. That left the nuclear atom to neutrals, to Bohr and his assistant Hendrik Kramers; and also to Arnold Sommerfeld, who, though far from neutral, was too old to fight, and spent the war continuing the work on the quantized atom he had begun before it. These men together with a few colleagues accomplished wonders. Physicists demobilized in 1919 were astonished by what Bohr and Sommerfeld had made of Rutherford's unpromising nuclear model while they were otherwise engaged.

Rutherford might well have shared in the astonishment. Even before the war his younger colleagues had gone too fast for him. He had put forward his model as a scattering theory, nothing more. This was in keeping with general attitudes toward micro-models. Developed to represent a limited range of phenomena, they were not expected to be widely competent; examples include Lorentz's model of the Zeeman effect, Planck's resonator, Kelvin's atom, and various versions of the electron theory of metals. While Rutherford's group strove to make his model fundamental to physics and much of chemistry, he worried that its extension far beyond its original application would undercut its plausibility as a scattering theory.

The leading men in his group needed self-confidence beyond the ordinary measure of physicists to persevere against his doubts. It is probably relevant to their relations with him that Rutherford, whose father farmed flax in New Zealand, came from a lower social class than they did. With one exception they were sons of university professors, who, in those days, ranked with generals and admirals. The exception, Hevesy, was the most privileged of them all, being the titled son of a baroness and an industrialist ennobled by the Emperor of Austria-Hungary, Franz Josef I.

I'll devote the rest of my talk to indicating how the interlocking work of Rutherford's prewar group returned the electrons to the atoms from which his scattering theory had stripped them and made the nuclear atom basic to understanding the microworld. To stay within my time and close to the centennial we are celebrating, I'll take the story only up to the outbreak of WWI.

2. Interlocking research

Hevesy arrived in Rutherford's laboratory in Manchester under orders of his professor, the celebrated Fritz Haber, to learn something about radioactivity. Rutherford had recently received a shipment of radium D, a radioactive remote descendent of radium, incorporated in a useless mass of lighter lead. As Hevesy told the tale, Rutherford assigned him the task of liberating the radioactive nuggets from the inert mass with the encouraging words, "my boy, if you can't do this you are worthless as a chemist." Hevesy labored prodigiously, but to no avail; as in several other cases then known, none of the tricks of the chemist could isolate the activity. Hevesy concluded that if a Jewish-Hungarian nobleman with the best education money could buy could not effect the isolation, neither could God. It followed that the correspondence between atomic weight and chemical properties supposed in the periodic table of elements had exceptions.

Hevesy shared this insight with Bohr, who also had come to Manchester to learn about radioactivity. Bohr was then very receptive to ideas about atomic structure, as he was engaged in a critical review of a paper by Darwin related to new scattering experiments by Geiger and Maraden designed to confirm the nuclear model. Since these experiments had to do with the slowing of alpha particles in passing through matter, which involves interactions with bound electrons, Darwin had to make assumptions about the manner of energy transfer between the alpha particle and the atom's electronic structure. Bohr thought that Darwin's assumptions were unphysical and tried to replace them by an analogy to dispersion: a passing alpha particle would transfer energy by making the electrons oscillate around their equilibrium orbits. In trying to calculate the energy exchanged in this way, Bohr discovered for himself the radical *mechanical* instability of the nuclear atom.

Reasoning in his peculiar style, Bohr regarded this obstacle to calculation as a further indication that the nuclear model contained or represented deep truth; for in his thesis on the electron theory of metals, he had identified problems that indicated limits to the applicability of ordinary mechanics to the microworld. The nuclear atom, in contrast to the model with which J.J. Thomson had advanced atomic theory, suffered from the same sort of limitations he had found in his thesis. Bohr guessed that nature preserved atoms by making use of the restrictions, whatever they might be, represented by Planck's constant *h*; and, consequently, that *h* somehow fixed the dimensions of atoms.

Bohr interpreted Hevesy's report about the inseparability of lead and radium D as another indication, indeed, perhaps, the most persuasive indication, of the general correctness of Rutherford's model. The distinction between the charge on the electronic structure and the weight of the nucleus offered the possibility of distinguishing the seats of chemical and radioactive processes. It was not atomic weight, but the total charge on the electronic structure of a neutral atom, that determined the place of the element in the periodic table. The forces, whatever they might be, that made isotopes and regulated radioactive decay, operated in the nucleus. Whereas Rutherford had ignored the electronic structure in order to have clean collisions between point nuclei, Bohr ignored radioactivity, which he locked away in the nucleus, in order to concentrate on the magnetic, chemical, and spectroscopic properties of the orbiting electrons.

Meanwhile Moseley and Darwin had annoyed Rutherford by proposing to apply to atomic problems the technique of x-ray spectroscopy then recently invented by Max von Laue and the William Braggs, father and son. After winning Rutherford's grudging approval to study with the elder Bragg, Moseley learned enough to enable him to continue on his own with his famous measurements of the frequencies of the K and L lines. The frequencies he measured for the strongest K line for a dozen metals agreed with the developing notion of atomic number, since they increased in an orderly way with the charge on the nucleus, without any modulation from the electronic structure. Evidently, Moseley and Bohr concluded, the production of K lines took place so deep inside the atom that it was controlled entirely by the charge on the nucleus. In one case, cobalt and nickel, where ordering by weight reverses the chemical sequence, Moseley found that his formula confirmed the chemistry, that is, ordering by atomic number Z, rather than by atomic weight A.

While Moseley worked the deep simple spectra of complicated atoms, Bohr made his spectacular conquest of the complicated spectra of the simplest atoms. He did not begin by writing down the now familiar condition on the angular momentum, for that would have meant proceeding without analogy to Planck's theory of radiation, the exemplar of the quantization process. But since, contrary to the simple harmonic oscillator, which Planck took as his model, in the nuclear atom frequency is not independent of amplitude, Bohr could not take over Planck's oracular formula $E = h\nu$. Also in Planck's case, the frequency of the radiation emitted is the same as the frequency of the oscillator; but the nuclear atom, with its many electronic frequencies, defines no single emission frequency. This is not the place to rehearse how Bohr by guess, intuition, and, perhaps, poetic inspiration, arrived at the concept of stationary states characterized by the condition that in falling into the *n*th orbit from infinity an electron would radiate away an amount of energy equal to its kinetic energy in the orbit; and that this radiant energy should exist as a quantum of frequency *n*⎨/2 or maybe of *n* quanta each of frequency ⎨/2, where ⎨ is the mechanical frequency of the *n*th orbit. This condition amounts to the usual restriction on angular momentum in the orbit, but is evidently conceptually far different from it.

With this quantum condition and the ordinary mechanical balance between electrostatic and centrifugal force in the orbit, Bohr was able to derive the Rydberg constant in terms of fundamental constants. The derivation also required the rule, for which there was no authority but the stability of atoms, that in its normal or ground state an electron did not feel the small perturbing forces that caused the catastrophic oscillations Bohr had discovered in examining Darwin’s theory. The same protection had to be extended to excited states if electrons in them were to preserve their energy until they radiated it away while descending to a lower state.

According to the Balmer formla interpreted by Bohr as an energy equation, the lines of the hydrogen spectrum satisfying it are emitted in a transition from the *n*th to the second orbit. That was too much for Rutherford. He demanded to know how an electron was to divine the frequency at which it was to radiate before it knew its destination. Bohr replied that Rutherford wanted to know too much. The radiation process was unitary and indivisible, with no defined or definable middle. Bringing in the electron structure demanded the admission, somewhere, of an hypothesis at odds with the classical theory of orbits on which the structure otherwise depended; except, of course, in the extreme case of the hyperbolic orbits Rutherford had calculated, where the structure does not figure.

2. Prewar conquests

Augmented by the concepts of isotopy and atomic number, divided into precincts for visible radiations, x rays, and radioactivity, and quantified against mechanical and radiative collapse, Rutherford’s nuclear atom made contact with key questions in physics and chemistry. As we know, in its original form and function, it did not carry conviction, especially on the continent, where many physicists had expressed skepticism about atomic models in general. But the Bohr-Sommerfeld atom, with its extraordinary quantitative performance and qualitative appeal, changed many minds, notably Sommerfeld’s, about which, as it is now the property of Suman Seth, I’ll say nothing more.

The most important confirmation of the Bohr-Rutherford atom acquired before the war concerned the spectrum of ionized helium, whose structure, according to Bohr, was half-way between those of a helium atom and an alpha particle. Spectroscopists had ascribed certain lines they had found in stellar spectra to hydrogen because they satisfied a Balmer-like formula, though with half-integers rather than whole ones. Bohr reassigned them to ionized helium, which, according to his theory, should have had a Rydberg constant four times that of hydrogen. With this hint, spectroscopists detected the lines of interest in discharge tubes containing helium without hydrogen. The ratio of the Rydbergs turned out to be 4.0163. Bohr turned the discrepancy into a miracle for true believers by redoing his calculations taking into account that the nucleus is not infinitely heavy in comparison with an electron. That introduced a small correction factor involving the ratio of the electronic to the nuclear mass. It raised the ratio of the Rydbergs from 4 to 4.0160, and the perplexity of atomic physicists to infinity. For how could the most literal application of ordinary mechanics to a non-mechanical atom produce numbers that agreed with experiment to five significant figures?

There were other unexpected corroborations as well, like the Stark effect, the Franck-Hertz experiment, and Moseley’s formulas. With these things in hand, Bohr and his brother Harald, already a well-known mathematician though younger than Niels, toured German physics institutes touting the quantized nuclear atom. Hevesy also told everyone he knew about its power. The advertisements were not merely theoretical. Hevesy had the idea of turning the chemical identity of isotopes to advantage, and invented the method of radioactive tracers. About the same time, Moseley recognized that the regular increase in frequency of the K lines from one element to the next in the periodic table enabled him to identify the chemical makeup of any compound from which he could coax out K lines; and also to specify where elements remained to be discovered.

Rutherford acknowledged that his model atom could not have convinced physicists at large without the contributions of his coworkers. In his last lecture before his sudden death in 1937, he said, “it is not in the nature of things for one man to make a sudden violent [revolutionary!] discovery; science goes step by step, and every man depends on the work of his predecessors.” He had the development of the nuclear atom in mind. Of all the relevant steps he and his coworkers then took, he rated Bohr’s theory as the most important by far. As he put it, his scattering theory set the stage for a world-historical performance: for he rated the work of Bohr as (and these are his words) “one of the greatest triumphs of the human mind.”

Perhaps because we have cone to assume that atomic models should have general applicability throughout wide domains, we do not find the quick success of Rutherford’s nuclear atom as remarkable as we ought. Why should so simple a model, invented for a specific and limited purpose, have been so singularly fruitful? Especially as we now regard it as hopelessly inadequate in its quantitative parts and, as a picture in time and space, with particles in visualizable orbits, altogether misleading, a monument to the hubris that conceived the microworld of our thought as a miniature version of the macroworld of our senses. Bohr puzzled over the problem, and, in a moment of despair over difficulties of the old quantum theory, lamented that the quantized nuclear model had been so successful. The success had allowed physicists to disregard its fundamental inconsistencies and implausibility and to slog on complacently calculating when they should have been worried about why their efforts paid off.

From these considerations we can construct a reason in addition to the passage of 100 years to celebrate the centennial of Rutherford’s invention, or rather, reinvention of the nuclear model of the atom. It took courage, optimism, and confidence as well as insight and cleverness. To go further, Rutherford relied on younger people with the same moral qualities. They were there, in his laboratory, when the chance came. They were there, able to pursue their own course at their own pace even against his wishes, because he had been confident enough to surround himself with the ablest coworkers he could find.

In noticing the centennial of the nuclear model of the atom, we should remember not only its invention and the push it gave to physics, but also the moral qualities of its first developers. In their ability to advance atomic physics in loose but peaceful collaboration, in their optimism and confidence, and in their relative indifference to the bottom line (for neither Hevesy nor Moseley so much as thought of patenting his analytical method), Rutherford and his coworkers still have something to teach us.