Historical Background: Atoms

Introduction

The concept of the atom is fundamental to our modern scientific understanding of the world. The eminent physicist Richard P. Feynman opined, in the introduction to the first of his lectures on physics, that “[i]f, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words? I believe it is *the atomic hypothesis* (or the atomic fact, or whatever you wish to call it) that *all things are made of atoms—little particles that move around in perpetual motion, attracting each other when they are little distance apart, but repelling upon being squeezed into one another*” (Feynman et al. 1963, I-3). The statement is relevant to the historical background of the atom in that Feynman is clearly pointing out how important the concept of an atomic structure of matter is to modern science. Implicitly, he raises another issue that is germane to an analysis of its genesis. In speaking of the “atomic hypothesis (or the atomic fact, or whatever you wish to call it),” Feynman both identifies and ignores a crucial detail: the existence of the atom as either a hypothesis or fact and which part of the description is which. Feynman ignores the issue by leaving the decision of what to call “it” to the reader—an apparent crude form of relativism that could possibly be explained by its early 1960s publication date. Considering the time period, it is doubtful whether a different position could have been expected either from an epistemological or nature of science perspective. Such a statement is somewhat annoying from today’s point of view; however, it illustrates the degree to which knowledge about the nature of science has developed in recent decades.

In order to teach the concept of atomism, one must recognize another important aspect in its historical development—that the concept of a chemical element is a prerequisite for the formulation of the atomic model. This can be seen in the historical analysis both in Greek antiquity, as well as for the modern period. It can also be identified in the educational conceptions. The historical development of the concept of elements is beyond the scope of this background material.

Ancient discussions about the structure of matter

The question of how the material world is structured was already discussed in Greek antiquity, the knowledge of which was, in part, transferred from this period to the Early Modern Era in Europe.[1] In this respect, the topic of a fundamental element that constitutes all the other substances becomes relevant; however, it is, of course, not synonymous with a simplistic atomic concept, as this fundamental element could exist without any corpuscular structure. Philosophers such as Thales of Miletus, Anaximenes, Heraclites, and Empedocles were among those scholars who promoted their respective conceptions. Around 450 BC, two philosophers, Democritus and Leucippus, proposed ideas that are applicable to the introduction of the concept of the atom. Both postulated that the material world is composed of very tiny particles which can not be separated into smaller parts and are distinguishable from each other by their shape and size. According to Democritus, these atoms move in empty space and collide with each other. By creating specific combinations of atoms, other substances are formed. These combinations are not permanent, and the atoms can separate again. The concepts of Leucippus and Democritus were, however, not accepted by their contemporaries because

> [t]wo factors weighed against any widespread acceptance of the classical version of atomism. The first factor was the uncompromising materialism of this philosophy. By explaining sensation and even thought in terms of the motions of atoms, the atomists challenged man’s self-understanding. Atomism seemed to leave no place for spiritual values. Surely the values of friendship, courage, and worship cannot be reduced to the concourse of atoms. Moreover, the atomists left no place in science for considerations of purpose, whether natural or divine. The second factor was the *ad hoc* nature of the atomists’ explanations. (Losee 2001, 25)

Additionally, there was a rival concept of the four elements, which appeared to be superior in that it explained the behavior of all existing matter, as well as its properties, through the elements of water, air, fire, and earth.[2]

A central, if not the central, figure for the rejection of the atomic theory was Aristotle, who advocated the four-elements theory and added a fifth element—

[1] There is evidence that models of the material world existed in the Indian culture, as well as in Babylonian culture; however, documentation of these concepts is poorer, and they have not played any role in the introduction of an atomic theory into European science; thus they are not discussed in this background.

[2] It has to be understood that these elements were not what we call earth, fire, air, and water, but they are elementary principles (see also the background on the development of the Periodic Table).

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ether—which filled the space between the celestial bodies. According to Aristotle, no empty space could exist due to the *horror vacui*, that is, nature's "fear" of emptiness. He believed that everything in nature is intentional and that there is no superfluous action in nature. Additionally, each object has a natural position, and, if displaced, it aims at getting back to this position. Using his principles, Aristotle was able to explain observable processes. The atomists were not only unable to propose a superior explanation, but they assumed the existence of invisible particles, which was Aristotle's major criticism against the atomic theory, apart from not accepting the idea of empty space, which contradicted his theory. He also found the notion of an object being in permanent motion absurd. He opposed the atomic concept in its entirety, as it stood in contradiction to several of his core beliefs. Despite this, Aristotle still remains important to the modern development of the atomic theory because the original works of Leucippus and Democritus were lost and are known only through Aristotle's criticism.

Aristotle's works were kept and expanded in the Islamic culture, and through this culture, they came back to Europe and the Christian culture. During the scholastic period, this modified Aristotelian understanding became dominant, particularly as it was considered to be coherent with the Bible. With time, astronomers, and later natural philosophers, developed a different understanding of natural processes. Consequently, Aristotle's authority was increasingly questioned throughout the 17th and 18th centuries, and, at the end of this period, it was the experimenting, enlightened natural philosopher who was thought to be able to uncover the laws and structure of nature. In this process, some experiments and considerations were developed that seemed to strengthen the ancient atomic hypothesis. Of particular importance was the demonstration of the existence of a vacuum.[3] Another argument used was that if a tiny piece of incense is burned, it can be smelled throughout the room. As the room is significantly bigger than the space the incense initially occupied, the initial piece has to be divided into more than 750,000,000 parts. These calculations were intended to show how small the particles have to be that form the piece of incense (see Beer & Pricha 1997). Such a discussion, however, remained on the level of simple calculations, and there was no claim whatsoever about the existence of atoms or the nature of their properties.

Understandings of the latter kind were only developed in the early 19th century.

Structuring matter: Dalton

During the genesis of modern science, probably the first scholar to establish an atomic conception was John Dalton, a chemist who followed Lavoisier's new, quantitative approach to chemistry. The use of a balance to analyze chemical reactions formed a major achievement of Lavoisier's new chemical system, and this enabled chemists to take a different perspective on chemical reactions. Several times, Lavoisier, himself, established the difference between classical chemistry and his novel approach, for example, as documented by Nye: "Lavoisier wrote in the *Opuscules physiques et chimiques* (1774) that he 'applied to chemistry not only to the apparatus and methods of experimental physics but also the spirit of precision and calculation which characterizes that science'" (1993, 35). Yet, it was not only the methodological step or conceptual modifications that made Lavoisier's chemistry distinct from the previous understanding. Two key aspects in his understanding of chemistry were the different notion of chemical reactions that helped him to use the quantitative description and the understanding that "simple substances" can be interpreted as elements that cannot be decomposed any further. In this respect, Lavoisier stated explicitly,

> I shall, therefore, only add upon this subject, that if, by the term *elements*, we mean to express those simple and indivisible atoms of which matter is composed, it is extremely probable we know nothing at all about them; but if we apply the term *elements*, or *principles of bodies*, to express our idea of the last point which analysis is capable of reaching, we must admit, as elements, all the substances into which we are able, to reduce bodies by decomposition. (Lavoisier 1794, xxiii)

Remarkably, Lavoisier was already using the term "atom" even though he was not employing an atomic theory. The notion of the element in Lavoisier's statement is noteworthy in the emergence of the atomic theory.

A key understanding resulted from the quantitative observations at the end of the 18th century: that compounds are the result of the reaction of specific ratios of masses of the elements that form the compound. This rule became known as the law of constant composition. Even though this law appeared to be valid for the chemical reactions that had been analyzed quantitatively, there was another striking aspect, first characterized by Dalton. He realized that there were some chemical reactions in which different compounds were formed through a combination of the same elements (e.g., from a reaction of copper with oxygen, two differ-

[3] For some of the controversies with respect to the existence of a vacuum and the related philosophical implications, see Shapin and Schaffer 1989.

ent compounds can result; likewise with carbon and oxygen, and so on). The resulting compound depended on the amount of the two initial substances that reacted with each other. There was another regularity that Dalton noticed, namely, that there was a ratio of small integer numbers between the masses of element A that reacted with the same amount of element B to form two different compounds. From this finding, Dalton formulated another law: the law of multiple proportions. This law states that if two elements react with more than one compound, then the masses of element A reacting with the same amount of B are small integer multiples. This law, together with the law of constant composition, formed the beginning of the stoichiometric approach in chemistry.

While the law of multiple proportions was based on empirical evidence, it was not the only conclusion that Dalton drew from his experiments. In a lecture delivered at the Royal Institution of Great Britain,[4] he proposed the following ideas, which form the basis of the modern atomic theory of matter:

All matter is composed of atoms
Atoms cannot be made or destroyed
All atoms of the same element are identical
Different elements have different types of atoms
Chemical reactions occur when atoms are rearranged
Compounds are formed from atoms of the constituent elements.[5]

Evidently, Dalton's use of the term atom is different from that of Lavoisier's. Dalton's conception of atoms is characterized, among other things, by their countability and their having a certain weight, while in Lavoisier's conception, their chemical properties are more pertinent, and it is even unclear whether the atom is an actual particle.

These assumptions enabled Dalton to devise an explanation of the stoichiometric laws which he and others had formulated. According to this understanding, the law of constant composition results both from the realization that all atoms of the same element are identical and that chemical reactions are a result of the rearrangement of the atoms. The law of multiple proportions can then be interpreted as being the outcome of different arrangements of atoms that result in different compounds. In the interpretation, the knowledge about quantitative chemical analysis became based on the first paradigm, in the Kuhnian sense, arguably turning this achievement in stoichiometric chemistry into a science. Yet, acceptance was not automatic. Even though Dalton's theory was quickly adopted by several chemists, others rejected it. A key problem was the assumption that each element was formed by a different atom, resulting in the identification of about thirty different atoms at the beginning of the 19th century, with the number increasing. Thus, instead of simplifying the structure of matter, Dalton's atomic theory made nature more complex. Despite this criticism, the stoichiometric laws were used by chemists, some of whom used common fractions to express the ratio of masses, implying that there was no indivisible particle. This was not just a problem of initial acceptance, as reservations against this theory were still stated explicitly even sixty years later. In 1869, the President of the Chemical Society, Alexander William Williamson, stated in a speech "… that on the one hand, all chemists use the atomic theory, and that, on the other hand, a considerable number of them view it with distrust, some with positive dislike" (quoted in Tilden & Glasstone 1926, 227). Some renowned chemists and physicists still rejected the atomic theory as late as the beginning of the 20th century. Especially for chemists, though, the atom became an entity that was used in their analysis of chemical reactions; however, it was not considered to be real (neither in the positivistic sense, nor in the sense of an applicable theoretical description) but just a heuristic tool to describe chemical reactions, without contributing to the actual understanding of matter (Görs 1999).

The atom gets established

While some chemists accepted the atom as a useful hypothesis, physicists began to use the atom as a real entity with explanatory power. In particular, the developing science of thermodynamics played an important role in the establishing of a physical atom, which is crucial for kinetic theory, since atoms in motion represent heat. The realist interpretation was, nevertheless, strongly criticized, particularly in the German-speaking scientific community, by eminent scientists such as Ernst Mach, Wilhelm Ostwald, and Georg Helm.[6] The controversy between these prominent researchers, especially Ostwald (a Nobel Prize winner in 1909) and Mach, and the proponents of a statistical interpretation, most notably Boltzmann, was not just based on physical issues, but involved deep, philosophical questions. A key question was whether individual atoms were visible

[4] According to Clarke (1803), the first presentation was made at the Manchester Philosophical Society.

[5] http://www.rsc.org/chemsoc/timeline/pages/1803.html, last access April 18, 2012

[6] For other reasons, Max Planck, too, initially criticized atomism as he understood it in Boltzmann's statistical interpretation (see Müller 2008). This discussion was not limited to the German speaking community; another example of the opponents of atomism is Poincare.

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and whether there was any evidence for the existence of individual atoms.

At the beginning of the 20th century, it appeared that the atomic theory was being overthrown, and Boltzmann's view was considered to be a remnant from the 19th century. The situation changed significantly, however, when Planck's theory of radiation was established and Einstein and Smoluchowski published their interpretation of Brownian motion. This phenomenon had been described by several observers in the 18th century but was attributed to the biologist Robert Brown, who, in the early 19th century, noticed that small pollen and dust particles floating on water moved in an erratic manner. The remarkable detail about this motion of lifeless particles was that it appeared never to stop. For about half a century, the interpretation of this motion remained an open question. Even though towards the end of the 19th century some researchers proposed solutions to this question which correspond to our current-day interpretation, it was only between 1905 and 1906 that Albert Einstein and Marian Smoluchowski, independently, presented their mathematical analyses of Brownian motion. In fact, Einstein's article was one of the three famous papers in his *annus mirabilis*, the other two concerning the photoelectric effect and the special theory of relativity. Both researchers explained that Brownian motion could be caused by the kinetic energy of the water particles. The explanation appeared to be the first macroscopic effect necessitating the use of the assumption of small particles, thus forming empirical evidence for the kinetic theory and, therefore, for the atomic theory, as well. Ostwald is said to have been convinced of the adequacy of the atomic theory on account of the agreement between its description and the empirical data. At about the same time, another example of empirical evidence proved the adequacy of the atomic theory, one which was said to have convinced Mach: when radioactive particles were placed next to a fluorescent screen, minute flashes of light could be observed, which were interpreted as the result of individual α-particles. Thus, within a few years, the understanding of atomism that had been almost completely rejected was almost completely accepted. Boltzmann, the great proponent of the atomic theory, however, did not experience the general acceptance of the theory for which he had fought, having committed suicide in September of 1906.

The atom gets a substructure

Even before Einstein's and Smoluchowski's work helped to establish a consensus about the accuracy of the atomic description of matter, some researchers established empirical results that actually contradicted the initial understanding of the atom as being indivisible. In fact, Faraday's work on electrolysis from the 1830s could have raised questions about the fundamental and indivisible nature of the atom as formulated by Dalton. According to Faraday's investigation, a certain amount of electricity released a certain amount of an element in the process of electrolysis; however, this empirical result did not raise questions about the atomic nature of matter. On the contrary, it remained unclear until well into the 20th century whether electricity had an atomic structure or whether the ratio between electrical charge and released matter was the mean of several reactions that could occur simultaneously. Only with the recognition of Millikan's measurement of the elementary charge by means of the Nobel Prize in the 1920s was this issue settled, at least for the vast majority of scientists (see Holton 1978).

Towards the end of the 19th century, other evidence was produced that questioned the indivisible character of the atom. In actuality, the starting point was research that, in retrospect, could be taken as further evidence for the atomic theory even though it was not interpreted as such, historically. In the 1860s, the chemist Bunsen showed, together with the physicist Kirchhoff, that the light emitted from a substance was highly characteristic of the material and that only special frequencies (or lines, if the spectrum were analyzed) were emitted or absorbed. This also provided a method for identifying new elements, causing the number of elements to increase significantly over the next few years. The analysis of spectra was a major question and expanded into the analysis of cathode rays and their interaction with gases in tubes. Experimentalists, thereby, hoped to develop a further understanding of the constitution of matter (Müller 2004). Particularly, the analysis of cathode rays appeared to be promising. Among the researchers working in this field was J. J. Thomson. He analyzed cathode rays and established that they were formed by particles[7] which had a mass of about 1/1000 that of the hydrogen atom. He was also able to determine the mass to charge ratio by deflecting the particles in a magnetic field. More importantly, he experimented with different cathode materials to emit the rays which were ejected when heating up the cathode and then accelerated with an electric field. Thomson showed that

[7] Quite remarkably, his son, George Paget Thomson, was also awarded the Nobel Prize in physics, this time for his work on electron diffraction. In some sense, it could be (admittedly oversimplified) argued that J. J. Thomson was awarded the Nobel Prize for demonstrating that electrons were particles, while his son was awarded the same honor for demonstrating that electrons are not particles but that they have a wave character.

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all the particles had more or less the same properties, regardless of which cathode material was used. This could be seen as an indication that these particles (corpuscles, as he called them) were a fundamental constituent of matter. It was, however, problematic to imagine a stable atom containing these light-weight, electrically-charged corpuscles. Thomson finally arrived at a solution: "We suppose that the atom consists of a number of corpuscles moving about in a sphere of uniform positive electrification …" (Thomson 1904, 255).[8] The implication of this hypothesis was that the atom was no longer indivisible and that the model of the atom would have to be modified.

With the emergence of the field of radioactivity in the early 20th century, another modification of the atomic model became necessary. One of the researchers who established his scientific career by analyzing radioactivity was the Nobel Laureate, Ernest Rutherford, a physicist from New Zealand, who undertook his early research in Canada and then moved to England. In the Cavendish laboratory, two of his assistants—Geiger and Marsden—carried out the experiment to scatter α-particles from a metal foil (Geiger & Marsden 1909).

Rutherford had already suspected that scattering is possible when he had observed the passage of α-particles through sheets of mica. This experiment was taken up again, and the result was most disturbing, even though not entirely unexpected. In the course of the experimentation, Geiger and Marsden used gold foil, as this could be made extremely thin. They observed that even though the vast majority of α-particles passed through the metal foil, with some of them being scattered, a few of them were reflected. Heilbron observes that

> [i]n retrospect, Marsden's discovery was the 'most incredible event' that had ever happened to him [Rutherford, PH], almost as incredible, he would say, as if a fifteen-inch shell fired at a piece of tissue paper bounced back and hit the gunner. That the military imagery and the incredulity are later fabrications we can see easily from a lecture Rutherford delivered …six months after the discovery of the diffuse reflection. (1981, 264f.)

The result of the experiment was certainly unexpected in the scientific community, and Rutherford formulated an explanation that was, likewise, unanticipated: he calculated, from the behavior of the α-particles, that the atom had a small, positively charged nucleus that contains almost all its mass, while most of the space of the atom was empty, except for the electrons that moved around somewhere in this space.

[8] Actually, the Japanese physicist Nagaoka had formulated a similar solution one year earlier.

Atoms can change

While Rutherford became famous for his research into radioactivity, the first researcher to observe radioactivity was the French physicist Henri Becquerel. One can use the term "discovery" to characterize his initial observation, as it was completely unexpected, even though some awareness of radiation effects certainly existed due to Röntgen's demonstration of X-rays. His discovery opened a new scientific field, which was not entered immediately by him or other scientists since the rays emitted from uranium salts were merely considered to be a curiosity not worth any further scientific attention. It was the young Polish chemist, Marie Skłodowska, collaborating with French physicist, Pierre Curie, who actually brought this new field to the forefront. Marie and Pierre Curie argued that within several radioactive samples elements other than uranium had to exist, as the radiation was stronger in the other samples than the one emitted from pure uranium. In a long and laborious analysis, they were finally able to prepare pure samples of the elements polonium and radium which were identified through their spectra. Radium, in particular, became central to the research performed in the new field of radioactivity because of its being fairly active and producing rays different from those of uranium. It became evident that many more chemical elements had the ability to emit such radiation. There were several more astonishing findings, among them the transformation of one element into another in the process of an α- or a β-decay, recounted in the following anecdote:

> Rutherford and Soddy found, for example, that radioactive thorium, atom by atom, was gradually turning itself into radium. At the moment he realized this, Soddy … blurted out, 'Rutherford, this is transmutation!' 'For Mike's sake, Soddy,' his companion shot back, 'don't call it *transmutation*. They'll have our heads off as alchemists.' (Weart 1988, 5f.)

Already, the work of the Curies had established a fundamental idea: that the radiation of a material is related to some properties of the element. Uranium emitted a different type of radiation than polonium and radium, and so on. Moreover, through the experiments, it was realized that the activity of a sample decreases over time, which is apparent when the transformation of the atoms into those of another element is taken into consideration. A problem with respect to this decreasing activity was the half-life not being a value that could be used for an individual atom. The law of radioactive decay worked only for a statistical sample, and a prediction of the behavior of an individual atom was not possible. Initially, this was taken to be an indication that atomic physics only required further development;

however, in the end, it became clear that predicting the behavior of a single atom is simply not possible and that decay can only be described mathematically in terms of the statistics of the ensemble.

In the analysis of radiation, three different types were identified and soon characterized. Surprisingly, the α-rays turned out to be nuclei of helium, an element that, until then, had been detected only in the sun with spectroscopic methods and seemingly did not exist on Earth. That α-rays were positive particles while the β-rays were negatively-charged electrons meant that not only could the negative substance be emitted from the atom, but also some of the positive substance.

Physical atoms and chemical atoms

Determining the properties of the different rays was one of the first tasks that experimenters took on once it became apparent that radioactivity would become a significant research area. Among other things, the mass and charge of the particles that formed the rays were determined. This was done by applying a well-defined magnetic field perpendicular to the direction of the rays. From the deflection, the charge to mass ratio could be determined. A comparable set-up was used to analyze atoms, which provided another insight into their structure and solved one of the remaining problems. Particularly through the work of Francis Aston, who modified the charge to mass ratio set-up into a mass spectrometer, it was realized that even though from a chemical point of view all atoms of an element were indistinguishable, from the physical point of view, this was not the case. Aston demonstrated that for several elements, different atoms existed that could be distinguished only by their mass. This helped to explain why certain elements had an atomic weight that was not an integer multiple of the mass of the hydrogen atom. From Aston's data, it became evident that the atomic weight was the weighted mean of the mass of the constituent atoms, already predicted and referred to as isotopes by Soddy, Rutherford's collaborator. This calculation made it apparent that the atomic weight of each individual isotope was, within a certain accuracy, an integer multiple of the hydrogen atom.

Atoms can be changed

While most experiments with radioactive substances were aimed at analyzing the radiation, some researchers attempted to modify the atoms (called artificial transmutation). Initially, α-particles were used and were shot towards matter. It was observed that some atoms were able to integrate the α-particle into the nucleus, thus forming a new element. The first to establish this experiment was, again, Rutherford, who showed that when α-particles were sent through nitrogen, hydrogen and oxygen were traceable. Rutherford's interpretation was that the nitrogen nucleus was absorbing an α-particle and the newly formed nucleus immediately emitted a hydrogen nucleus. This was the first successful attempt to modify an element and to create a new one, which was followed quickly by other such experiments. It must, however, be understood that this was not nuclear fission—something still considered to be impossible.

Rutherford named the hydrogen nucleus a proton and postulated that this proton was an elementary component of all nuclei. That the mass of the nuclei did not form integer multiples of the mass of the proton was still problematic. Two remaining questions were why the positive protons could form the nucleus and how a β-decay could be explained. Rutherford assumed that electrons also existed in the nucleus and formed pairs together with protons and that these pairs could keep the elementary particles in the nucleus together.

Among the researchers who tried to investigate the nucleus and the atom through interaction with α-particles were Irène Joliot-Curie (daughter of Marie Curie) and her husband, Frédéric. They repeated some experiments which had been carried out in Berlin. Irradiating beryllium with α-particles, they observed a significant amount of radiation, which they initially assumed to be γ-rays. The particles of this radiation were not charged and appeared to have an extremely high amount of energy. Even though not charged, these particles could interact with hydrogen and release electrons. While the Joliot-Curies maintained that the interpretation of the result of their experiments was γ-radiation, James Chadwick, who was working with Rutherford, chose a different interpretation. According to him, this radiation could be explained with a new corpuscle, resulting in a completely new type of radiation. Further experiments showed that the particles had a rest mass similar to that of the proton and could be seen as the particle replacing the proton-electron pair, which Rutherford had assumed to explain the relative stability of the nucleus.

The neutron enabled further experimentation on transmutation, as the absence of a repulsive electrostatic force eliminated the problem of attempting to get an α-particle into the nucleus and enabled the creation of new radioactive isotopes and new products of decay. Among the researchers in this field were the Joliot-Curies in Paris, Fermi in Italy, and Hahn and Strassmann in Berlin. All aimed at injecting a neutron into the nucleus of uranium, the heaviest known element at that time. The objective was to produce the so-called transuranium elements, ones with a greater atomic number than uranium, which seemed to be the only possibility of developing new elements, as the periodic table was considered to be complete.

Of the researchers, Hahn, a chemist, was most dissatisfied with his results: It appeared that through his experiments uranium had been turned into barium, which had significantly less atomic weight than uranium. Hahn addressed this issue in a letter to his former, long-time co-worker, physicist Lise Meitner, who had shortly before relocated to Sweden, fleeing from the threat of fascist Germany after the so-called Anschluss of Austria. Meitner responded initially that such a result did not seem to be plausible,[9] but, as she pointed out in the same letter, there had been so many surprises in the history of radioactivity that one could hardly say that this or that was impossible. Hahn insisted that he had verified barium, and Meitner pointed out in another letter, written a couple of days later, that at least in the context of energy, fission could have occurred. In a discussion she had with her nephew, Otto Frisch, Meitner formulated the idea that the model of the atom possibly had to be thought of like a drop: if an object with adequate energy hit that drop, the impact would break it into two smaller ones.

Together with Strassmann, Hahn finally published his findings and pointed out that for him, as a chemist, he had to state that the resulting isotopes behaved like barium; yet, he claimed that from the point of physics he was still not convinced that this element could be produced in such an experiment. Views on this changed very quickly, and scientists immediately pointed out that in such a reaction not only would a significant amount of energy be released, but other neutrons as well, allowing for the possibility of a chain reaction.

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[9] Before these experiments were carried out, however, the concept of nuclear fission had already been formulated by Ida Noddack in 1934 when she was criticizing the discussion of Fermi in his experiments on transuranic elements.

[10] Some audio files with protagonists such as Thomson, Rutherford, Hahn, etc. are to be found at http://www.aip.org/history/mod/fission/fission1/01.html

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