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The scientific and cultural role of atomistics

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Abstract The development of the idea that atoms are the building blocks of matter is presented. This hypothesis began in the Ancient Greece and, independently, in the Ancient India. Arguments are presented that the fact that the atomic theory started in these two regions and not e.g. in Egypt, China or by the Mayas can be linked to their writing. In both Greece and India the alphabet contained letters and not pictograms as used in the three other cultures.

The role of Islamic scholars in preserving the knowledge of the ancient atomic theories is presented. In the Middle Ages a significant part of the Greek philosophic treatises have been firstly learned via the Arab translations. It is shown that the atomic concept has not been developed in the Middle Ages. This was because the church found it to be in a disagreement with the Holy Scripture.

The start of the modern scientific atomic theory is presented and the role of the established quantitative laws of chemical reactions is discussed. Arguments are presented that the atoms discovered in the nineteenth century did not have the qualities of the atoms proposed by the Ancient Greek philosophers. Contrary to the atoms proposed by the Greeks the former can be decomposed into more fundamental parts.

The discussion of the possibility that quarks, leptons and quanta of interactions fields meet the above qualities is presented.

Key words atom • history of science • structure of matter

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Two words of the title of this lecture have not well defined meaning. They are “atomistics” and “culture”. The Dictionary of the Polish Language [1] gives two meanings to the word “atomistics” (in Polish – atomistyka). The first one is “the ancient philosophical system according to which the world is built from an infinite number of small indivisible particles – atoms”. The second one says “activities concerning the use of the atomic energy for peaceful applications”. In the present lecture the stress will be put on the first of the two meanings. The only difference will be that now “atomistics” is not a philosophical system but the well established knowledge.

And what is the meaning of the word “culture”? Its origin is the Latin word “cultura”. It means “agriculture”. Already in ancient times Cicero defined the philosophy as “cultura animi”, which means “the culture of the mind”. If the philosophy is a culture, so is the atomistics, which has been developed by philosophers.

Today “culture” means, first of all, the artistic activities such as music, painting, theater, literature, architecture,… However, the fast development of science and education makes knowledge also a part of culture. This includes also the natural sciences and with them the atomistics. In fact, educated people are usually aware that matter is composed of atoms.

The contribution of atomistics to culture means its own development and achievements. Sometimes it influences also the art. Its discoveries and achievements inspire, e.g. painters or writers. Certainly, the writers of science-fiction books are inspired by scientific ideas, among them also those dealing with atoms. However, to contribute to culture they must be careful not to cross the thin border between fantasy and nonsense.

Primordial matter

The idea that matter is composed of atoms arose twenty five centuries ago. However, it was not the first attempt to understand matter. Matter appears in millions of different forms. Are they completely independent? Can we understand them? Such questions have been asked some thousands years ago in Ancient China, India and by the Greeks in the Mediterranean region. Ancient thinkers were strongly convinced that human mind is able to understand matter. The first step for that consideration was to reduce the number of material forms by selecting only those most important. They were supposed to be the origin of the rest of matter. These most important forms were called the primordial matter.

The Ancient Greece

Thales of Miletus (*ca*. 620–540 BC) was the first Greek philosopher who introduced the idea of the primordial matter. He maintained that the origin of all matter is water. There is no life without water. Moreover, water is the only substance which is able to turn into ice and into air (vapor). So it should be able to transform itself also into other forms of matter.

We do not know how Thales has imagined the transformation of water into other forms of matter. His arguments were obviously not convincing enough, at least for his pupil and successor Anaximander (*ca*. VII–VI BC). For him, the primordial matter was an invisible, unlimited, eternal and unchangeable substance – apeiron. Other philosophers were less metaphysical. They were choosing as the primordial known forms of matter such as air, fire or earth.

The final selection of the primordial matter has been introduced by Empedocles from Akragas (*ca*. 492–432 BC). According to him, the primordial elements of matter were fire, water, earth and air. These were subsequently accepted by Aristotle and, embedded in his physics, remained in science for more than two thousands years.

The Ancient India

The idea of a primordial matter existed not only in Greece. The Hindu philosophy introduced this idea probably in the sixth century BC. The Hindu elements were the same as proposed by Empedocles – fire, water, earth and air. They were completed with ether and sometimes with less materialistic ones: time, space, soul and thought. Interesting is the coincidence of the first four Hindu elements with those of the Greeks. Some historians suggested that the two choices were not independent. At present, this suggestion is rather rejected.

Table 1. Primordial elements of matter in antiquity

Culture	Primordial elements of matter
Greek	fire, air, water, earth
Hindu	fire, air, water, earth, and also ether, time, space, soul, thought
Chinese	wood, fire, earth, metal, water

The Ancient China

The influence of the Hindu or Greek cultures on the choice of the primordial elements by the Chinese can be excluded. The reason is not only the distance and the Himalaya Mountains which separate China from India and the Mediterranean region. The decisive factor is that the Chinese theory of five elements is much older than primordial elements in India and Greece. The theory says that there are five primordial elements: wood, fire, earth, metal and water. It is interesting that the Chinese have not chosen the air, which is so important for the life.

Historians say that the theory of five elements is very old, older than the Chinese writing.

All the three important ancient cultures have stated that the gigantic variety of material forms emerges from very few ones (Table 1). This was a very important and brave simplification in the attempts to study matter.

Atomistics in Antiquity

Ancient Greece

Contrary to the contemporary atomistics the atomic hypothesis of the Ancient Greek philosophers was not based on experiments. It was formulated as the result of logical considerations and discussions. An important problem discussed by philosophers was whether a portion of matter can be divided into smaller parts without any limitation. If there is a limit to the division, then there exist small parts of matter which cannot be further divided. They have been called atoms – indivisible grains of matter. The theory that all matter is composed of atoms has been formulated in Ancient Greece first by Leucippus who lived in the fifth century BC, and by his pupil Democritus born in Abdera *ca*. 460 BC. Unfortunately nothing was preserved in the written form from Leucippus and practically nothing from about eighty treatises of Democritus. Their atomic theory is known from descriptions by other philosophers, mainly Aristotle and his school. According to Democritus, the world is composed of atoms and the void, where atoms are moving. Atoms are very hard and cannot be destroyed or altered. They have various dimensions and shapes.

The idea that a vacuum exists was very hard to accept. The everyday experience was showing that it could not occur. The existence of a vacuum was the most often criticized concept of the atomic theory.

The atomic theory of Leucippus and Democritus has been developed and reformulated by Epicurus (*ca*. 341–271 BC). According to him everything is made of atoms, also the human body and the soul. The movement of atoms can be stochastically altered. This introduces accidents and is the origin of liberty.

The description of the atomic theory of Epicurus we owe to Roman philosopher and poet Lucretius (97–55 BC) who presented it in his poem “De rerum natura”. Lucretius was the last important atomic philosopher of antiquity.

Ancient India

The atomic picture of the world has been formulated not only in Ancient Greece. According to a Hindu legend in the sixth century BC, philosopher Kanada, the founder of the Vashieshika philosophic system, presented the idea that matter is composed of small, indivisible grains, “parmanu”. It is not sure whether Kanada is a historical person. In any case the idea of parmanu (atoms) can be found in the Vashieshika-Sutra written between VI and II century BC.

Is it possible that Democritus, who probably visited India, learned the atomic theory from Hindu philosophers? There is no indication for that. This would be totally excluded if the Vashishika-Sutra text on atoms were dated later than 370 BC i.e. after the death of Democritus.

Why atoms were conceived in Greece and India and not elsewhere?

Why the concept that matter is composed of atoms occurred in Greece and India but not in Egypt, China or by the Mayas? In all these regions the development of culture, political organization and living standard were on a comparable level. What was it that differed Greece and India from the other three regions? A possible explanation could be the structure of their writing. The Greek and Hindu (Dawanagari) alphabets were composed of letters whereas the other three alphabets used pictograms which represented entire words or concepts. There is some analogy between words written with letters and pieces of matter made of atoms. The use of letters in writing could be a model for matter composed of atoms [3].

Atomistics from the beginning of our era until the nineteenth century

Atomistics in the Islamic culture

After Epicurus the atomic theory of matter remained essentially unchanged for the subsequent two thousand years. Unfortunately, many original treatises and other writings have been lost. Their content is partially known from the writings of other philosophers. An important role in preserving the ancient knowledge was played by Aristotle, who opposed the atomic theory of Leucippus and Democritus, but in his writings presented their views. The atomic theory of Epicurus was described by Lucretius. Many original works of the Greek philosophers have been captured by the Arabs when they conquered territories at the eastern and southern coast of the Mediterranean Sea. The Islamic scholars were very impressed by the science of Ancient Greece. Many treatises have been translated into Arabic. There were even dedicated schools for translations. Several centuries later the medieval scholars in many cases learned the ancient science not from the Greek originals but from the Arabic translations.

Many schools of the Islamic science accepted the atomic theory of the ancient Greek philosophers. There was no contradiction between Islam and the concept of atoms. It does not mean that there were no disputes among Islamic scholars. Arguments have been exchanged to prove different points of view. However, repressions were very rare. Sometimes they were addressed to all scientists as, e.g. in the Cherson region where the most active scholars, atomists and anti-atomists, were expelled and cursed in mosques.

The Islamic scientists did not develop further the ancient theory of atoms. The exception was the notion of a substance. Generally, they agreed that a single atom is not a substance. To form a substance more atoms are needed. We share this point of view. We know that the collection of many atoms shows qualities which cannot exist in a single atom e.g. the emission of the laser light.

Atomistics in the Middle Ages

The scientific activity in Medieval Europe was rather scanty, but there existed schools and active scientific centers. One example was the cathedral school in Chartres. It developed from the episcopal school and in the twelfth century became the well known intellectual center. The main activity was the liberal arts and the natural sciences. The Chartres scholars were studying treatises of ancient and Islamic scientists. Wilhelm from Conches lectured on the atomic theory of Democritus. At that time it was not forbidden. However, he encountered certain difficulties.

The Medieval science was dominated by Aristotle. Due to his concept of the “first cause” of movement, which could be identified with God, his teaching was approved by the Roman Church. Aristotle did not accept the existence of atoms. Therefore, atomic theory was later banned by the Church. In spite of that, one can list about fifteen medieval scholars, who accepted and supported the concept of atoms. Some of them are listed below.

- St. Isidor of Sevilla (*ca*. 560–636), bishop of Sevilla,
- Thierry de Chartres (died 1155), chancellor of the episcopal school in Chartres,
- William of Ockham (1300–1350), lecturer in Oxford; later, to avoid trial, he moved to Munich,
- Nicolas of Autrecourt (1300–1350) was forced to retract his views and to burn his writings,

– Vincent de Beauvais (died *ca*. 1264), author of an encyclopedia,

and many others.

Sometimes it was dangerous to support atomic views. Giordiano Bruno and Galileo were prosecuted and condemned, the first to be burned, the second to life imprisonment, which happened not only for propagating the heliocentric theory of Copernicus but also for supporting the theory of atoms.

Pierre Gassendi (1592–1655) is often called the reviver of atomic theory. In his time in Paris the law forbade, under the capital punishment, the critics of Aristotle. Any statement in favor of the atomic theory was considered as such a criticism [4]. P. Gassendi managed to avoid this fate because he was protected by influential friends. In 1649 Gassendi published the treatise "Syntagma philosophiae Epicuri" in which he presented his atomistic views. According to him, atoms could not be created nor destroyed. They are hard and have the weight and the size. Gassendi stressed that the existence of the important component of the atomic theory, the vacuum, has been demonstrated experimentally by Evangelista Torricelli. This was the first, although not direct, experimental evidence in favor of the atomic theory. According to Gassendi, Torricelli has shown that the vacuum is a physical reality and not only the concept invented more than two thousand years ago by the Greek philosophers. However, one had to wait for the next two hundred years for more direct experimental evidence that atoms exist.

Contrary to the views of ancient philosophers Gassendi maintained that atoms were created by God and they move not by themselves but according to the God's will. It was the first step towards the reconciliation of the atomic theory and the Roman Church.

The beginnings of the modern scientific atomic theory

The merit to found the scientific atomic theory of matter goes to John Dalton (1766–1844). However, it was Antoine-Laurent Lavoisier (1740–1794), who prior to Dalton, contributed significantly to the discovery of chemical laws, which demonstrated the existence of atoms. Lavoisier has shown that water, which for twenty five centuries was considered to be one of primordial elements, is, in fact, the mixture of the two more fundamental forms of matter – hydrogen and oxygen. The theory of the four primordial elements was destroyed. The four elements of Empedocles and Aristotle were replaced by a few tens of chemical elements.

When decomposing water Lavoisier noticed that the ratio between the weight of hydrogen to that of oxygen was always one to eight. However, he did not elaborate on this observation. The introduction of gravimetric analysis (measurements of weights) to chemistry was the most important contribution of Lavoisier to this science. As the result of gravimetric analysis he formulated the "law of mass conservation" in chemical reactions. It stated that the sum of weights of reacting components is equal to the sum of weights of reaction products.

After many measurements of weights of reacting substances, Joseph-Louis Proust (1754–1826), another outstanding chemist, established "the law of constant proportions". It says that when two components react they combine always in the same proportion of weights. The gravimetric analysis led to the formulation of more laws which related weights of the reacting components and the products of chemical reactions. The analyses of the established chemical laws and of their explanation have been presented by John Dalton (1766–1844) in his two volume treatise "A new system of chemical philosophy" published in 1808 and 1810. He has shown that the simple and natural explanation of the established laws is the hypothesis that all elements are composed of atoms specific for each element.

Subsequent experiments on the reactions of gaseous elements also showed regularities easily explained by the atomic theory. So it was with electrochemical reactions. By the end of the nineteenth century, after two and a half thousand years since it was postulated, the atomic theory was widely accepted. It was a triumphal success for chemistry.

It were not those atoms which we expected

The last years of the nineteenth century brought first indications that the discovered atoms were not those postulated by the ancient Greek philosophers. Their atoms were indivisible whereas the atoms discovered in the passing century apparently were not. The first signals that they may be decomposed came from the studies of electric discharges.

The experiments on electrical discharges in rarefied gases have shown that the cathode emits unknown "cathode radiation". It carried the negative electrical charge (C. P. Varley – 1871). In 1897 Joseph John Thomson (1856–1940) measured the electric charge to mass ratio of cathode ray particles. It was the same for different materials of electrodes and various gases. It became obvious that electric discharges can extract from atoms identical negative particles later named electrons. They were parts of any atom. The first elementary particle, more fundamental than atom, was discovered. It was the proof that atoms can be divided.

The next step in studying the atom's internal structure was to probe it with alpha particles emitted by radium or polonium. The discovery, by Maria and Pierre Curie, of these two elements was not only a big chemical achievements or an important discovery for cancer therapy. It also offered physicist a tool, the α rays, for studying matter. Ernest Rutherford (1871–1937) analyzed the scattering of α rays by a gold foil. In 1911 he realized that all positive charge of an atom and practically all of its mass were concentrated in a very small central region. Rutherford called this region the atom nucleus. In 1919 he discovered that the nucleus of the hydrogen atom is composed of a single, positively charged particle – a proton. The proton was, after the electron, the second elementary particle. However, these two particles – electrons and protons – could not be the only building blocks of atoms. It was difficult to accept that electrons are bound in a tiny atomic nucleus.

On the other hand, they were needed there to compensate the excess of the positive charge of protons. In order to explain the mass and the electric charge of atomic nuclei the third type of particles, neutral and with the mass close to that of protons, was needed.

James Chadwick (1891–1974) was studying the electrically neutral radiation emitted by boron bombarded with alpha particles. In 1932 he showed that the radiation was composed of particles with the mass nearly equal to the mass of protons. These particles were named neutrons.

After the discovery of neutrons it was very attractive to accept that the primordial matter is protons, neutrons and electrons. Atoms of all chemical elements were built from these three types of particles. Suddenly the structure of matter became extremely simple, even simpler than that of Empedocles.

According to Rutherford, an atom looked as a microscopic planetary system. In his model of atoms, the electrons, similarly to planets, were circulating around the heavy central body, the atomic nucleus, which was made of protons and neutrons. This model of atoms, in its general terms, is still in use. The only modification of the original formulation of Rutherford was forced by quantum mechanics. It diffused sharp electron orbits into orbitals.

In addition to three basic ingredients of matter, Albert Einstein demonstrated in 1905 that there exist quanta of the electromagnetic interaction. They were called photons and are a kind of atoms of the electromagnetic force.

Protons and neutrons are not the primordial matter

After 1932, new experiments and observations more and more undermined the belief that protons and neutrons are primordial and indivisible. The number of discovered elementary particles was gradually increasing. Some of the new particles could, equally with protons and neutrons, be components of atomic nuclei. This was shown by the two Polish physicists, Marian Danysz (1909–1983) and Jerzy Pniewski (1913–1989) (Fig. 1), who in 1952 discovered the atomic nucleus, which, in addition to protons and neutrons, contained a hiperon [2]. In fact, there exist about one hundred particles similar to protons and neutrons which are called baryons. None of them is more or less primordial than the others.

In 1962 two physicists, Murray Gell-Mann and George Zweig independently proposed that strongly interacting elementary particles, among them protons and neutrons, are made of more elementary grains of matter. They are now called quarks. The electric charge of all observed elementary particles, expressed in units equal to the charge of a proton, was an integer number. Quarks were expected to be different. Their electric charge was foreseen to be either +2/3e or –1/3e. The existence of quarks was confirmed experimentally in 1969 by Jerome Friedman, Henry Kendall and Richard Taylor and their team. They collided very energetic electrons with protons and looked how they are scattered. The results indicated that electrons collided not with a whole proton but only with small parts of its matter. The distribution of these parts, called partons, inside a proton was found to be independent of the energy of incoming electrons and the scattered angle. The distribution is an internal characteristics of a proton. Very soon partons have been identified as quarks introduced by Gell-Mann and Zweig.

Fig. 1. The Polish physicists, Marian Danysz (1909–1983) and Jerzy Pniewski (1913–1989) who discovered a hiperfragment, an atomic nucleus built from protons, neutrons and a hiperon; picture taken *ca*. 1963.

Protons and neutrons turned out not to be the most elementary blocks of matter. Both are composed of three quarks. A proton contains two u-quarks with the electric charge +2/3e and one d-quark with the charge –1/3e. The composition of neutrons is somewhat different. A neutron contains one u-quark and two d-quarks. Atomic nuclei composed of protons and neutrons are in fact made of u-quarks and d-quarks. The structure of matter which surrounds us remains very simple. Atoms are composed of only three components: u- and d-quarks and electrons.

The further studies of matter increased the number of quarks to six, three with the charge +2/3e and three with the charge –1/3e. One can arrange them in pairs as shown in Table 2. Electrons have received two companions, muons and taons. All these particles carry the electric charge – e. There are also electrically neutral particles, neutrinos. They are nearly massless. Together with electrons, muons and taons neutrinos form the family called leptons (in Greek – light). All together there exist twelve different elementary grains of matter – six quarks and six leptons (Table 2).

Table 2. Elementary components of matter

Quarks	+2/3e	u (up)	c (charm)	t (top)
	–1/3e	d (down)	s (strange)	b (bottom)
Leptons	0	ν_e	ν_μ	ν_τ
	–e	e (electron)	μ (muon)	τ (taon)

Table 3. Quanta of interactions – "atoms of forces"

Interaction	Quant	Quant mass
Electromagnetic	photon	0
Strong	gluon	0
Weak	bosons W^+ and W^- boson Z^0	86 proton masses 97 proton masses

"Atoms of forces"

This year we celebrate the hundredth anniversary of the discovery of photons, the quanta of the electromagnetic interaction. They are like atoms of the electromagnetic force.

There are still other forces. We know the nuclear force, which keeps protons and neutrons inside atomic nuclei. The nuclear force is the source of the energy produced in nuclear power stations and, unfortunately, also the energy of atomic explosions. This very intense force is only a shadow or a remnant of the gigantic force, that bounds quarks in, e.g. protons and neutrons. The interaction between quarks is called strong interaction. Its quanta are massless and electrically neutral. They are called gluons.

There is also the "weak interaction" acting between all twelve components of matter, quarks and leptons. The weak interaction is very local. This is because its quanta are heavy. There are three of them – one neutral, Z^0 and two charged, W^+ and W^-. Their masses are nearly equal to the mass of hundred protons. All quanta of interactions discovered so far are listed in Table 3.

Have we reached the limit of divisibility of matter?

This question can never be answered. The answer would be rather our conviction and not a firm statement. It is always possible that a grain of matter, which now seems to be indivisible, can later be cut into smaller parts with new, now unknown, tools. Nevertheless, there is an argument to believe that quarks and leptons mark the limit of the divisibility of matter. First of all, the number of types of quarks, which is usually called the number of quark flavors, is not very big. Six flavors is just sufficient to generate an excess of the matter over the antimatter in an indirect but simple way. Due to this excess, when the matter and antimatter annihilated, enough matter was left for the existence of the Universe. The situation was different with chemical elements and with "elementary particles". They were too numerous to be primordial. Among quarks none of them is a spare one. All of them are needed.

However, we have to realize that all the story here presented concerns the "visible matter" which we can study in details. The structure of the Universe tells us that it is a small part of the matter. What is the rest of matter existing in the Universe, how it looks and out of what it is built remains to be learned. Following the scientific intuition of ancient philosophers we expect that the invisible matter will be understood as well.

The closing words

We are fortunate to witness the incredible progress of the understanding of matter. We have to lower our heads before the wisdom and the intuition of ancient philosophers, who many years ago initiated this long way of learning the matter. We have also the duty to convey to our younger colleagues the existing knowledge, enriched according to our abilities.

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