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Looking into (the) Matter

Scientific Artefacts and Atomistic Iconography

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It is probably a myth that the history of science and the history of scientific objects are converging enterprises that eventually will coincide in one comprehensive historical account of the scientific endeavor. Clearly, the history of looking into matter of various kind can be presented as a history of artefacts that allowed for new insights into these kinds of matter whether it was with a microscope, a NMR spectrometer or a particle accelerator. Despite of the fact that this is what science museums could do best (and probably should) the prevailing mode of discourse subordinates the history of looking into matter to those of thinking about matter and of conceptualizing matter in general. In this way philosophy and imagination often ruled over matters of fact.

To make things even more complicated recent historical scholarship has put forward that besides the perspectives of matter theories and their conceptual development on the one hand and that of experimentation involving scientific artefacts on the other hand there is also a third point of view: the history of images or rather of atomistic iconography.[1] What separates these perspectives are the respective claims of autonomy, i. e. that each one corresponds to an independent tradition not affected by more or less radical changes in one of the other fields. Theory tradition, iconographic tradition and object tradition, for short, form different layers of scientific development with certain stabilizing connections much like the brick-wall metaphor of Peter Galison's history of particle physics.[2]

I focus in this article on the question how the understanding of the nature of matter developed – mostly in the 20th century – using the terms "looking/perceiving" and "image" in a wider sense. As for atoms they have been pictured as balls, modeled along the analogy of planetary systems of mechanical machinery or mentally perceived as ethereal structures or fields.

After a short sketch of the iconographic perspective and its claim of exhibiting invariant structures of knowledge I will ask to which extent also the history of artefacts could claim autonomy and the power to define knowledge structures for our understanding of matter. Before I can begin to deal with this question, however, I have to point to one more distinction

[1] See e. g. Wolfgang Lefèvre/Jürgen Renn/Urs Schöpflin (eds.): The power of images in early modern science, Basel 2003; Arthur I. Miller: Imagery and representations in twentieth-century physics, in: Nye, Mary Jo: The Cambridge History of Science, Vol. 5: The modern physical and mathematical sciences, Cambridge 2003, 191-215; Bruno Latour (Hg.): Iconoclash. Beyond the image wars in science, religion and art on the occasion of the exhibition Iconoclash Karlsruhe, Karlsruhe 2002.

[2] Lefèvre et al. *Powers* (Note 1), write: "(…) the striking independence of this tradition of visual representations from specific theories of matter (…) points to the fact that these theories comprise structures of knowledge invariant with respect to the great conceptual revolutions of science.", VIII. Peter Galison: Image and logic. A material culture of microphysics, Chicago 1997.

regarding the status of artefacts. Two sorts must be separated that both inhabit our museums: those artefacts primarily manufactured for scientific research and those built as didactic means for mostly representing otherwise gained knowledge.[3]

Images (of) Matter

It is one of the main tasks of a historian of scientific objects to identify their contemporary role within the scientific development and to remove the retrospective interpretations and categorizations applied to them as much as possible. This, however, also applies to the second type of artefacts. Take the "atomic models" manufactured for the department of atomic physics at the Deutsches Musuem that demonstrate the atomic conceptions of Democritus and Lucretius. Do they reflect the atomic iconography of antiquity or the Roman empire?

Fig. 1 a) and b)*: Atomic models made for display at the Deutsches Museum. Source: Deutsches Museum, Archive (DMA), BN R949/05 and 02.

Beyond doubt Democritus was one of the early atomists, though we do not have many genuine sources of his teachings. It is in the writings of his junior by three centuries, Lucretius, where we find the text that gave rise for the atomic models of Fig. 1. In the second chapter of his *On the Nature of Things* (De rerum natura) we read:[4]

> Thus simple 'tis to see that whatsoever
> Can touch the senses pleasingly are made
> Of smooth and rounded elements, whilst those
> Which seem the bitter and the sharp, are held
> Entwined by elements more crook'd, and so
> Are wont to tear their ways into our senses,
> And rend our body as they enter in.

Though this seems to be a clear account of atomic modeling, and the widespread German translations are even more unmistakably speaking of "smooth and rounded atoms", i.e. spells out the indivisibility property, a look on Lucretius original lines shows immediately that the case is at least not this clear. The term element appears in his educational poem, referring to elements like fire and water but also to some primordial objects (primordial rerum), but not at this place. There is even made mention of the possibility of "larger elements" in olive oil

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[3] Clearly, this is not a sharp distinction; artefacts can also change their role between these two categories. The balls and wire construction kits widely employed in chemistry in the last third of the nineteenth and in the twentieth century may serve as an example for an ambiguous object. The table croquet balls of August Hoffmann (in the Museum of the History of Science in Oxford) or the colored cardboard models of Jacobus van't Hoff (in the Deutsches Museum) clearly had a different status than the metal plates and rods of Watson and Crick in they doble-helix structure (in the London Science Museum). Cp. Christoph Meinel: Molecules and croquet balls, in: Soraya de Chadarevian/Nick Hopwood: Models. The third dimension of science, Stanford 2004, 242-276; Christian Sichau: Atome. Eine lange Geschichte, in: Alto Brachner et al., ed.: Abenteuer der Erkenntnis. Albert Einstein und die Physik des 20. Jahrhunderts, München 2005, 142-151; Soraya Chandarevian: Portrait of a discovery. Watson, Crick and the double helix, Isis 94 (2003), 90-105.

* Figures are found on a table following this text.

[4] In the often reprinted translation of William E. Leonard, online at http://classics.mit.edu/Carus/nature_things.html.

some lines before, thus contrasting with the primordial objects that for itself should be free of color, taste etc. Here the lines read:[5]

> ut facile agnoscas e levibus atque rutundis
> esse ea quae sensus iucunde tangere possunt,
> at contra quae amara atque aspera cumque videntur,
> haec magis hamatis inter se nexa teneri
> proptereaque solere vias rescindere nostris
> sensibus introituque suo perrumpere corpus.

The appearing *ea quae* meaning *the ones that* (i.e. objects, items, things, maybe bodies, shapes etc.), however, leaves much room for interpretation and obviously what we read in the English or German translations is to some extent not from Lucretius but from the translators understanding of atomism of his time.

The point I want to make here is not to claim that the model presented to the visitors of the Deutsches Museum is actually wrong, nor is it necessary to evaluate how much we can hope to learn from an educational poem which still ranks poetic form and language higher than a rather austere exactitude. It is rather that there were no models or images in Democritus or Lucretius writings! We have to understand (and probably also to "exhibit") that there were times in history without pictorial representations of the contemporary matter concepts.[6]

The invention of atomist iconography

Only in recent years Christoph Lüthy has demonstrated convincingly that there was no atomistic iconography before the late 16th century. In particular his search for atomic representations in more than 70 editions of Lucretius text that were printed between the late 15th century and the early 18th century brought to light only a number of dramatic illustrations but no graphic representations of constituents of matter.[7]

What made the emergence of the globular atom impossible through the Aristotelian and scholastic tradition was a particular kind of anti-atomism. For Aristotle natural bodies appeared continuous and homogeneous and while they corresponded to certain "forms" this did not entail that pictures could be drawn, since these "forms" – as distinct from "figures" (figura) – meant logical principles, i. e. forms of thinking, rather than graphical figures or images. Though geometry played some role, here again the idealized relations of the (mathematical) geometry of forms were of interest not the physical geometry of nature. The scholastic tradition then did not add many illustrations which rather remained "notoriously few" but only "seemingly endless commentaries".[8] In the cases where images appeared they graphically illustrated relations, inclusions or hierarchical orderings, like the widespread onion-ring model of ordered inclusions.

[5] Lines 402-407 of the second book.

[6] This point clearly pertains to the recent work on the historicity of basic epistemological notions of science like fact, objectivity and rationality, cp. e. g. the collection of articles by Lorraine Daston: Wunder, Beweise und Tatsachen. Zur Geschichte der Rationalität, Frankfurt 2001, and the current research focus on the history of observation at the Berlin Max-Planck-Institute for the History of science.

[7] Christoph Lüthy: The invention of atomist iconography, in: Lefèvre et al. (note 1), 117-138, on 122. Here one illustration from 1683 is discussed in some detail which might qualify as depiction of atoms but then dismissed.

[8] John E. Murdoch: Album of science. Antiquity and middle ages, New York 1984, x, cited from Lüthy, Invention, note 7, 135.

With the Renaissance also the Platonic view resurfaced that saw a correspondence of the regular solids and the elements. While it is well known that Kepler took up this structure to describe the proportions of the planetary orbits in the solar system, no convincing relation was created between shapes and substances. Plato's attempt to relate wedge-shaped pyramids with fire could not convincingly be extended by early-modern thinkers.

Lüthy finally finds the full set of images of piled up globular atoms, the reference to Democritus and the use of the term "atom" in Giordano Bruno's 1591 *De triplici minimo et mensura*. This birth of atomic iconography, however, did not coincide with a revolution of a related theory of matter. Rather does one find Bruno's new imagery enmeshed in old theological, arithmetical and numerological speculations. Later natural philosophers like Kepler, Jungius or Descartes took away much of this historical baggage and reinterpreted the new iconography within their theory and philosophy. Cutting short a complex story, Lüthy proposed the following thesis:[9]

> "[T]he globular atom is an invention of the late sixteenth century. Neither did it exist before, nor did its invention seem very useful at first. Instead, the globular particle of matter is a strange outgrowth of Renaissance speculation which required decades of reinterpretation before it began to seem useful here and there as a possible tool for the explanation of certain natural phenomena."

I will in the following try to show that a thesis of this kind can also be put forward for twentieth century atomic imagery, when a similar invention of a new iconography has taken place, however, without being able to replace the globular atomic iconography fully in the public and in education, where it still lives on in its fifth century of existence.

Artefacts and new images of matter

Within the sciences new images of matter were clearly inevitable when experiment approached the realm of the atom. In particular the colorful phenomena of electrical discharges in evacuated glass tubes gave rise to a variety of images on what William Crookes called "the fourth state of matter". Interestingly, it were rather subatomic particles than atoms that became first visibly accessible through scientific artefacts.[10]

To illustrate the iconographic quality and persistence of the new images that originated in the late nineteenth century compare for a moment two typical images of matter from the beginning and from the end of the twentieth century which were both available for any interested audience.

Fig. 2: Drawing of discharge tube phenomena. Source: Detail from a plate of the sixth edition of Meyers Großes Konversationslexikon, Vol. V, Leipzig and Wien1905, facing p. 609.

Fig 3: OPAL event 51679 of run 10497 from 1998. Source: CERN, http://opal.web.cern.ch.

In the sixth edition of the popular German encyclopedia *Meyers Großes Konversationslexikon* that was published between 1906 and 1909 a full one-page colored plate with a number of drawings illustrated the entry on electrical discharge phenomena. The

[9] For Bruno's arguments and the reception of his writings see Lüthy, Invention, note 7, 123ff, quote on 118.

[10] I focus here mainly on the point of view physicists took towards the atom. For the respective approaches and interests in rich history of chemistry cp. e. g. Meinel, Molecules, note 3.

drawing given in Fig. 2 is particularly telling as it foreshadows much of the typical iconographic elements that physicist were still employing a century later in computer generated visualizations of particle accelerator experiments. In the *Konversationslexikon* one could read about this drawing:[11]

> When one attaches closely above a disk-shaped cathode an also disk-shaped anode with a hole in the center, then from this aperture a pencil of rays comes out that decomposes into three parts when a magnet is approached: an uninfluenced pencil of canal rays and two pencils of cathode rays, one traveling in the directions of the lines of force, the other on a trajectory of a spiral around the former.

Here we have, roughly speaking, all the elements of modern particle accelerator imagery: tracks coinciding in one point at different angles, their shape according to electric and magnetic fields and different colors identify different physical entities. The OPAL event shows a similar interaction of three lines, straight and spiral ones, both appear within a border given by the glass tube and the detector wall, respectively.

Hence we see that despite of the paramount progress physics has made on the fields of atomic and particle physics during the twentieth century and despite the magnificent development in scale and power of the experimental machinery during this time we find again a surprisingly stable iconography at least for this kind of representations of matter. In order to make the relation between scientific artefacts and atomic iconography more explicit I will consider a number of typical experiments of atomic physics from the first quarter of the twentieth century each of them involving a central scientific artefact.

I will place these object into two groups which I label as "looking at" and as "looking into" approaches. Looking at nature or pieces of matter means inspecting and viewing. This mode corresponds to the shiny part of experimentation like the light phenomena of electric discharges. The representations are photographic, depicting and take generally the phenomenon as a whole. Looking into matter as such or matter as a scientific problem, however, rather means exploring, investigating, studying, analyzing, preparing or even constructing. Its mode is more representational, graphic and selective, like the computer generated and deliberately colored displays of particle accelerator events. For a first characterization one may claim that the looking-at approach concerns questions of *visibility* while the looking-into approach concerns *visualizability*, i.e. the feasible ways of *visualizing*.

Looking at: Creating new limits of visibility

The puzzle of the existence of atoms and the microscopic(!) structure of matter has hardly benefited from the introduction and refinement of microscopes that revolutionized other fields, first of all biology. Only in the twentieth century avenues were found to cross the borders of microscopic resolution that fell short of the atomic scale. I will consider two artefacts in order to discuss the question to what extent it was actually possible to shift the limits of visibility by inventing new ways of looking at matter and to what extent scientists hoped to be able to see even into the atom. Both originated in the first two decades of the twentieth century, hence well before the advent of the electron microscope in the 1930s, that today dominates the imagery of the atomic scale and that has in recent time received much

[11] Meyers Großes Konversationslexikon, 6th ed., Vol. 5, Leipzig and Wien 1905, 609-619, quote on 614. The drawings probably originate from Otto Lehmann, cp. his *Die elektrischen Lichterscheinungen oder Entladungen, bezeichnet als Glimmen, Büschel, Funken und Lichtbogen, in freier Luft und in Vacuumröhren*, Halle 1898.

historical interest, in particular regarding the questions whether its images are mere constructions from abstract data rather than representations and who is in control of the pictures.[12]

Seeing the invisible: The ultra-microscope

It is a telling coincidence that in the same year 1872 when Ernst Abbe finished his theoretical work on image formation in microscopes Emil Du Bois-Reymond delivered his widely circulated *Ignorabimus* address at the Leipzig *Naturforscherversammlung*. While Abbe had arrived at firm foundations for his formula on the resolution limit of microscopes which entailed that structures finer than a fifth of a micrometer could not be seen though any such optical device, Du Bois-Reymond contemplated *On the limits of Science* in general, claiming finally that there are areas of knowledge besides the grasp of experimental research with scientific instruments: Not only were the mysteries of the human body and mind out of reach for the scientist, but also "confronted with the mysteries what matter and force were and how one could conceptionalize them, he must once an for all settle upon the much harder acknowledgeable truth: 'Ignorabimus'", i. e. we will never know.[13]

It is, however, an equally telling coincidence that shortly after the mathematician David Hilbert strongly rejected the ignorabimus mentality in his 1900 Paris address and made this a constant theme of his public lectures, Abbe's firm tried to create a new type of microscope which would transgress the resolution limit.[14] The 1903 ultramicroscope of colloid chemist Richard Zsigmondy and Zeiss instrument maker Henry Siedentopf represents a successful combination of interests: While Zsygmondy needed instruments for specific studies of colloids, in particular in order to determine the size of the colloidal particles and to see whether kinetic theory would be applicable, the young physicist Siedentopf, one of quite a number of young university graduates mostly in physics hired by Zeiss around 1900, represented a new scientific culture in the Zeiss Werke which became closely related to scientific research questions ranging from colloids, that bore potential application in optics, to possibly the existence of atoms in general.[15]

[12] Cp. e.g. Nicolas Rasmussen: Picture control. The electron microscope and the transformation of biology in America, 1940-1960, Stanford 1997, who demonstrates how involved the production even of seemingly plain pictures was. For this question with respect to the ordinary microscope see note 33.

[13] On Abbe's research and publications see David Cahan: The Zeiss Werke and the ultramicroscope: The creation of a scientific instrument in context, in: Jed Z. Buchwald: Scientific credibility and technical standards in 19th and early 20th century Germany and Britain, Dordrecht 1996, 67-115, on 72f. Emil du Bois-Reymond: Über die Grenzen des Naturerkennens, Berlin 1872, ^{7}1891, 51: "Gegenüber den Räthseln der Körperwelt ist der Naturforscher längst gewöhnt, mit männlicher Entsagung sein 'Ignorabimus' auszusprechen. (...) Gegenüber dem Räthsel aber, was Materie und Kraft seien, und wie sie zu denken vermögen, muss er ein für alle mal zu dem viel schwerer abzugebenden Wahrspruch sich entschließen: 'Ignorabimus'."

[14] David Hilbert: Mathematische Probleme, Archiv für Mathematik und Physik 3. Reihe, Bd. 1 (1901), 44-63 and 213-37, reprinted in David Hilbert: Gesammelte Abhandlungen, Vol. 3, Berlin 1935, 290-329, cp. also his 1930 Radio address as discussed in Victor Vinnikov: We shall know: Hilbert's apology, Mathematical intelligencer, 21(1999), 42-46. Cahan, Zeiss, note 13, 86f.

[15] Cahan, Zeiss, note 13, 90ff.

Fig. 4: 1903 ultramicroscope. Source: Ultramikroskopie für Kolloide. Nach Siedentopf und Zsigmondy (Zeiss Druckschrift Mikro 229), Jena, 3. ed. 1910, p. 5. DMA, Firmenschrift 503746.
The parts are labeled in the text as follows: a) table, b) optical bench, c) projection arc-lamp, d) aperture, f) first projection lens, g) precision slit head, h) second projection lens, i) microscope tripod, k) ground plate, l) cross sledge, m) screw.

As it was the Göttingen colloid chemist who had realized that it should be possible to observe with a microscope perpendicular to the direction of illumination and against a dark background diffraction cones of particles smaller than Abbe's limit (a phenomenon known as Tyndall's effect), it took actually one and a half years and the full support of Zeiss optical know-how orchestrated by Siedentopf to realize the rendering visible (*Sichtbarmachung*) of colloidal particles not visible before.[16] In principle the design of an ultramicroscope was quite simple, combining an ordinary microscope with an appropriate light source and an sample cell of favorable dimensions. Avoiding light to scatter into the dark background and focusing, however, turned out to be severe obstacles to be overcome by mechanical knowledge and skill; dark field condensers and the variant of the immersion ultramicroscope were developed in the following years.[17]

In their joint seminal paper Zsigmondy and Siedentopf reported that they "were able to make visible individual gold particles whose sizes were not very far from molecular dimensions".[18] Moreover, they demonstrated that, although strictly speaking what they observed were only diffraction disks, they still could make visible the particles themselves, as they could be separated, traced and also its size determined. Notably, the size of the diffractions disks photographed did not permit any conclusion about the actual particle size, which was assumed to follow from relating counted particle numbers per area with specific weight and colloid concentration.[19]

Naturally, the two authors were most interested to communicate the application of their method and discussed at length how the color of gold ruby glasses depended on the size of the now rendered visible gold particles. This may explain why they mentioned that their ultramicroscope would be "especially appropriate" for the study of Brownian motion only in passing and why they omitted any statement about the feasibility to make visible single atoms and thus proving their reality.[20]

It is generally understood that it was the second of Einstein's three 1905 papers that raised this question forcefully and it was in particular Jean Perrin who convinced both science and public of the reality of atoms.[21] Charlotte Bigg has stressed that the ultramicroscope as a

[16] For details ibid, for a brief sketch of the technical development in the following years see Andrew Ede: Microscope, Ultra-, in: Robert Bud/Deborah Warner, eds.: Instruments of science. An historical Encyclopedia, New York/London 1998, 400-401.

[17] Ede, Mikroscope, Ultra-, 400.

[18] Richard Zsigmondy/Richard Siedentopf: Über Sichtbarmachung und Größenbestimmung ultramikroskopischer Teilchen, mit besonderer Anwendung auf Goldrubingläser, Annalen der Physik 10 (1903), 1-39, quote on 2.

[19] Cahan, Zeiss Werke, 94ff.

[20] Zsigmondy/Siedentopf, Sichtbarmachung, on 10.

[21] Albert Einstein: Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen, Annalen der Physik 17 (1905), 549-560. Jean Perrin: Agitation

symbolic artefact on the one hand and as a practical device which allowed the demonstration of the movement of ultramicroscopic particles in agreement with the kinetic theory on the other hand served Perrin to present visual evidence for the existence of atoms without actually showing images of them.[22] Neither were ultramicroscopic particles single atoms nor did the photographs or projections presented depict particles as particles.

Still, the ultramicroscope not only pushed the limit of visibility – though not far enough to make visible single atom – its nicely observable diffraction spots of single particles furthermore changed the standards of acceptability so that its audience more or less believed to have seen atoms. To demonstrate how this happened, one could analyze in some more detail the notions used for photographs of indirect imaging methods like ultramicroscopy, X-ray diffraction or cloud chamber methods. In the popular German scientific monthly *Kosmos*, for example, a nice symmetrical Laue spot picture was presented in 1913 as "Atomphotogramm", thus suggesting that it would be something very much like a photographic image of a single atom; in 1917 a "photography of ultramicroscopic gold particles" of 15 nm size again pretended to be a true photographic depiction of the particles.[23]

Fig. 5 a) b): Source: Kosmos 10 (1913), 265, and 14 (1917), 94.

There is no need to discuss the well-known Laue experiment here in detail, which basically turned to invisible radiation of smaller wavelength in order to shift the limit of resolution (and replaced the eye completely with the photographic film). It may suffice to recall that the 1912 experiment was generally taken as having demonstrated the atomic nature of crystals unequivocally, though the direct relation of the spot patterns in Laue photographs with the arrangement of the atoms in a crystal was anything but immediate and Laue and collaborators needed some time and collegial advice to arrive at the proper interpretation of their photographs.[24] What they saw was, mathematically speaking, the reciprocal lattice of the crystal lattice. So one might say that as in the 1917 *Kosmos* where the notion of "ultramicroscopial seeing" (ultramikroskopische Sehen) was coined, the Laue experiment introduced a kind of "reciprocal seeing", which still represents special relations but e. g. falsify symmetry patterns.

While the ultramicroscope like the Laue method meant an extension of the traditional observation concepts one had to put up with certain distortions or, to put it more positive way, one had to learn new way of looking at nature. To which extent physicists believed to be able to push the limit of visibility will demonstrate my next example.

moleculaire et mouvement brownien, Compte Rendus de l'Académie des Sciences 146 (1908), 967, describes the projection of Brownian motion for public showing. Jean Perrin: Mouvement brownien et realité moléculaire, Annales de Chimie et de Physique 8 ser. 18 (1909), 1-114, deals comprehensively with the reality question. Cp. also Mary Jo Nye: Molecular reality: A perspective on the scientific work of Jean Perrin, London 1972.

[22] Charlotte Bigg: Brownian motion and microphysical reality c. 1900, Precirculated paper for the workshop on 'New path of physical knowledge: Science and the changing sense of reality c. 1900', Berlin 2004.

[23] H. Sieverking: Sichtbarmachung der Moleküle nach Laue und Wilson, *Kosmos* 10 (1913), 265-268, on 268, and Fritz Kahn: Das Ultramikroskop, *Kosmos* 14 (1917), 90-95, on 94.

[24] Paul Peter Ewald: Max von Laue 1879-1960, Biog. Mem. Fell. Roy. Soc. London 6 (1960), 135-156 on 137.

Hopes to picture the conceived: The origins of the Debye-Scherrer camera

The second artefact I would like to consider for the "looking at" category is the Deybe-Scherrer camera built in 1915 or 1916 to photograph – in some appropriate sense – the electron rings within the atoms, which Niels Bohr had proposed. In a paper presented to the Göttingen Academy of Science in early 1915, Debye attempted nothing different than the "ultra-microscopy of the interior of the atom." Presenting a theoretical discussion of X-ray scattering at randomly orientated Bohr type atoms and combining it with an appropriate interpretation of the Laue experiment he convinced himself, that "it must be possible in this way to establish by experiment the particular arrangement of the electrons in the atoms." And he concluded "whether, experimentally, rings are actually photographed or a continuous deviation from the scattering laws for dipoles is established" does not matter this much as long as "[it] appears to be essential that … we are in a position to measure from observations of the scattered radiation, the electron arrangement inside the atoms in centimeters."[25]

After this proposal which may remind us strongly to the language and procedures for the ultramicroscope, what followed was a story of failure to photograph the electron rings or the positions within the atom and a reinterpretation of this failure into an innovative and successful method for X-ray structure analysis of specimens that do not allow for lager crystals, which would have made them accessible with the Laue method.

Again the apparatus was in principle quite simple: an X-ray tube and a camera containing X-ray film. As Paul Scherrer later recalled, however, a number of obstacles had to be overcome:[26]

> Debye proposed to me that we try together such diffraction experiments. We used at first a gas-filled medical X-ray tube with platinum target which happened to be available in the collection of the institute. For power source we used an enormous induction coil with mercury interrupter and a gas-filled rectifying valve. The whole set-up appears nowadays like a show piece taken from a museum. The first diffraction photographs, with paper and charcoal as the scattering substances, showed no diffraction effects. The reason for this may have been that the thick glass wall of the tube absorbed the Pt L-radiation and transmitted only the continuous background. The film was relatively insensitive for the K-radiation, which, besides, was not strongly excited, so that possible maxima were covered up by the continuous background. This prompted me to construct a metal X-ray tube, water-cooled and with copper target. The tube remained connected to the rotating Gaede mercury pump. An aluminum window, 1/20 mm thick, permitted the rays to emerge. I also constructed a cylindrical diffraction camera, of 57 mm diameter, with a centering head for the sample, of the type which is being used still nowadays.

The camera is basically a cylinder with X-ray sensitive film affixed to the wall all way round. The sample has to be placed in the center and through a tube the monochromatic X-rays reach the sample where the interference patterns of diffracted radiation combine to cones that yield a pattern of curved lines on the film.

Fig. 6: Debye-Scherrer camera, formerly exhibited at the Deutsches Museum as "Camera for photographing powder diagrams with X-rays. Original from P. Debye and P. Scherrer, 1917".

[25] Peter Debye: Zerstreung von Röntgenstrahlen, Annalen der Physik 46 (1915), 809-823, english translation in Peter Debye: The collected papers of Peter J. W. Debye, London 1954, 40-50, on 41 and 50.

[26] Paul Scherrer: Personal reminiscences, in: Paul P. Ewald: Fifty Years of X-Ray Diffraction, Utrecht 1962, 642-646, on 642f.

It was provided to the Deusches Museum in Januray 1920 by Debye, Inv.-Nr. 47887.[27] Source DMA, BN 33581.

Did this artefact allow to photograph the electron rings in the atom? Debye and Scherrer reported on year later, that:[28]

> Experiments since then carried out by us show the respected result. However, in several instances, interference patterns of a different nature, and superimposed on the expected effect, were established, which indicated definitely by the sharpness of their maxima that the regular arrangement of the presumably small number of electrons in the atom cannot be held responsible for their occurrence. The present preliminary publication will be restricted to the description and explanation of this phenomenon. In a later publication we intend to treat the electron interferences ...

In quite a number of subsequent articles, which I cannot analyze here in detail, the authors more or less diffused their promise to come back to the "ultra-microscopy of the interior of the atom" and promoted their "method for the determination of the atom arrangement in crystals" instead.[29] When the *Handbuch der Experimentalphysik* covered in its 1928 volume on structure analysis by X-ray interferences also the work of Debye and Scherrer, reference was given only to a specific later publication in which the original aim of the experiments had disappeared.[30]

Debye knew what he wanted to see when looking at matter with his experiment. The photographic film, however, could not make visible what it should. Comparing this case to the later imagery electron microscopes provided, it may seem that the complex and widely adjustable ways in which these new devices produced images included one mode of representation that met the liking of the experimenter: landscapes of single atoms.[31] This brings us to our second category of the looking-into approach, since the electron microscope is already rather a hybrid than a pure looking-at device.

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[27] Letter Oskar von Miller to Peter Debye, 16. Jan. 1920, Archive Deutsches Museum.

[28] Peter Debye/Paul Scherrer.: Interferenzen an regellos orientierten Teilchen im Röntgenlicht I., Physikalische Zeitschrift 17 (1916), 277-83, translated in Collected Works, 51-62, on 51f. In Scherrer's recollection things read differently: "... Debye and I were most surprised to find on the very first photographs the sharp lines of a powder diagram, and it took us not long to interpret them correctly as crystalline diffraction on the randomly oriented microcrystals of the powder. The diffraction lines were much too sharp than that they could have been due to the few scattering electrons in each single atom. …" Scherrer, Reminiscences, note 26, 643.

[29] Cp. Paul Scherrer: Das Raumgitter des Aluminiums, Physikalische Zeitschrift 19 (1918), 23-27, on 23.

[30] Heinrich Ott: Strukturbestimmung mit Röntgeninterferenzen, Vol. 7/2 of Handbuch der Experimentalphysik ed. by Wilhelm Wien, 1928, 175, only refers to Peter Debye/Paul Scherrer: Interferenzen an regellos orientierten Teilchen im Röntgenlicht III (Über die Konstitution von Graphit und amorpher Kohle), Physikalische Zeitschrift 18 (1917), 291-301. This paper starts with a renewed description of the method in which silently the term "ultramicroscopy of the interior of the *atom*" as used in the first publication, was replaced with "ultramicroscopy of the interior of the *molecule*", on 291.

[31] For a discussion of this point for the case of the more modern scanning tunneling microscope cp. Jochen Hennig: Versinnlichung des Unzugänglichen. Oberflächendarstellungen in der zeitgenössischen Mikroskopie, in: Martina Heßler: Konstruierte Sichtbarkeiten. Wissenschafts- und Technikbilder seit der Frühen Neuzeit, München 2006, 99-116.

When Ian Hacking asked "Do we see through a microscope?", he basically concluded, yes. Acknowledging differences between microscopic and macroscopic seeing,[32] e. g. by the effects of diffraction, he still suggested that realism and the independent interference with various methods of otherwise not visible structures provide good reason to believe in the expansion of visibility. There may be some unclear territories like the question whether we can accept that the habit of crystallographers to discuss all their physics in reciprocal space (to which e. g. the Laue photographs relate) amounts to seeing their specimens in such an alternative space.[33] Nonetheless are the criteria mentioned for the looking-at category met, which comprise photographic nature, depicting quality and covering the entity as a whole.

Looking into: New attempts of visualization

Using a distinction Giora Hon introduced, the second type of experiments for exploring matter is related to the "bombardment method". According to Hon around the beginning of the twentieth century experimental physics underwent a "transition from the study of propagation phenomena to questions of structure" which was "reflected directly in the development of a new experimental technique that was conceived when physics turned its attention from macro- to microphysical problems." This bombardment method emerged, "when it became clear that rays and particles of known properties could be manipulated and used as probes that could impinge on, collide with, or plunge through the object under study."[34] How much this bombardment method changed the understanding of the atom already early in the atomic century can be seen from my third artefact.

From absorption measurements to the empty atom: Lenard's cathode ray tube

Claiming that a modern particle accelerator is in principle nothing else than the old cathode ray tube of the nineteenth century, one may ask since when did such a bold equation make sense and since when did scientists understand their tubes as particle stream sources that can be used to probe matter. First of all, the cathode rays were imprisoned in their glass tubes

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[32] The position that microscopical seeing were fundamentally different from macroscopical was already discussed intensely in the first half of the nineteenth century, cp. Jutta Schickore: Ever-present impediments: Exploring instruments and methods of microscopy, Perspectives on Science 9 (2001), 126-145.

[33] Ian Hacking: Do we see through a microscope?, in: Paul M. Churchland/Clifford A. Hooker: Images of science. Essays on realism, and empiricism with a reply from Bas C. van Fraassen, Chicago and London 1985, 132-152 (cp. also the comments of Bas van Fraassen on 297-301). The case of reciprocal space is discussed on 150. The invitation to the experimenter to verify what he or she sees by interference ("… you learn to see through a microscope by doing, not by looking", on 136) is a central issue of Hacking's philosophy of science, cp. Ian Hacking: Representing and intervening: Introductory topics in the philosophy of science, Cambridge 1983.

[34] Giora Hon: From propagation to structure: The experimental technique of bombardment as a contributing factor to the emerging quantum physics, Physics in Perspective 5 (2003), 150-173, on 152. While Hon judges an early paper of Rutherford and J. J. Thomson from 1896 on the effect of X-rays on the conduction of electricity in gases as the beginning of the bombardment methods (p. 153f.), I would prefer to argue that this should rather be associated with matter particles. Clearly, is does not make sense to create a priority conflict between Rutherford and Lenard here as their agendas were far to different, but the suggested understanding of Rutherford's 1896 experiments as "bombardment" of electrons with X-ray particles seem to me inconclusive.

and corresponding to the nature of the (necessary) gas filling of the tube a wide variety of colorful, but hard to describe and to classify phenomena occurred.[35] It was Philipp Lenard's merit to free the rays from their tube and let them penetrate a thin aluminum "window" and thus be available as pure rays that could serve for many purposes.[36] How the rays, however, escaped from the 1894 Lenard tube was far from clear. Were it oscillations like sound waves that could go through a membrane, were it phenomena of the immaterial, all-penetrating ether, or were it corpuscles or electrons, like the British physicists liked to believe?

Fig. 7 a) and b): Lenard tube of 1894 and drawing from laboratory notebook dated 22. Dec. 1892. Source: DMA, BN R5545-5 and BN 49844.

Lenard had combined his cathode ray tube with an observation tube so he could study the properties of the rays in vacuum, electric and magnetic fields and in the presence of arbitray substances (Fig. 7). When he started in 1895 to study systematically the absorption of cathode ray by many kinds of matter, ranging from hydrogen gas, paper and glass to mica, aluminum and gold, he was not yet convinced of the particle nature of his rays. Thus his universal law about the absorption of cathode rays, which he found, did not immediately relate to atomic theory of matter. The empirical law stated that the absorption power of any substance is independent of its particular physical or chemical properties and only depends on its density.

But when in the following years the electron emerged as a reality with measurable mass, velocity and charge, the propagation of rays became bombardments with particles. Lenard's measurements, which he extended in the following ten years, now meant through the particle interpretation that a) the electrons of the cathode rays can travel through thousands of atoms without absorption, that b) the rate of absorption depends merely on the density of matter, and that c) only for very slow electrons a higher than predicted absorption takes place, which points at electric forces in the atoms. In this way Lenard concluded from clear and undisputable experimental findings that atoms are almost completely empty, that their stability had to do with electric forces and that atoms could possibly consist of one type of primary matter which he called *dynamids*. In his seminal 1903 paper one reads:[37]

> For example, the volume in which one finds one cubic meter of solid platinum is empty – in the same sense like the cosmic space, that is traversed by light – save for *at most a cubic millimeter* as the complete true dynamide [corpuscle] volume.

Lenard's "empty" atom had most of the parts Rutherford's was later celebrated for.[38] The only thing, Lenard could not see with his electron bombardment method was whether the

[35] Cp. e.g. Falk Müller: Gasentladungsforschung im 19. Jahrhundert, Berlin/Diepholz 2004.

[36] Philipp Lenard: Über Kathodenstrahlen in Gasen von atmosphärischem Druck und im äußersten Vacuum, Annalen der Physik und Chemie 51 (1894), 225-267.

[37] Philipp Lenard: Über die Absorption von Kathodenstrahlen verschiedener Geschwindigkeit, Annalen der Physik 12 (1903), 714-744, on 739.

[38] Although only after Bohr combined it with quantum theory, cp. for the slow reception of Rutherford's paper John L. Heilbron: The scattering of α and β particles and Rutherford's atom. In: Archive for History of Exact Sciences 4 (1968), 247-307, on 300.

positive charge was concentrated in the center of the atom or whether pairs of positive and negative charge would fill the atoms, the alternative for which he opted.[39]

Lenard was probably the first to put forward the new paradigm for looking into matter, when he told the audience of his Nobel speech, which was later published in two editions, that[40]

> We can employ the quanta of the cathode rays as tiny probes, which we let pass through the interior of the atoms, so that they provide us with knowledge of this interior.

In this way, there is good reason to take Philipp Lenard at the turn of the twentieth century as founding father of this tradition rather than Rutherford ten years later, the more so as Lenard also introduced specific notions that originated from his absorptions researches like "cross section" for describing the probability to scatter particles at a target.

Despite of accurate numbers about impenetrable volumes and absorption behaviors, the new insights into the atom did not give rise to a clear picture. Like the old atomists, the knowledge of the atom – now experimental rather than philosophical – was unpictorial:[41]

> We are amazed at seeing, that we have got beyond the old impenetrability of matter. Every atom of matter claims in fact an impenetrable space with regard to the others; but with respect to the free quanta of electricity all sorts of atoms prove to be pervious structures, like built up from finer constituents with much space in between.

This does not mean that no models for the atom were discussed. Already around the time of the news of Lenard's findings the planetary analogy was cited by various authors in more popular journals – even by Lenard (through his assistant) –, but for physicists it was far too clear that the mechanical equilibrium that held for gravitation did not exist for the electrical forces which would immediately slow down a circulating electron. As a consequence, no drawings of these atomic conceptions appeared and it might be worthwhile to mention in this context that also Thomson's atomic model, now so prominent under the title of plum-pudding model, was neither put forward seriously with illustrations nor was it called this way.42 What happened to establish the planetary atom was a rather long negotiation process between science and public that eventually came to agree on accepting Bohr's quantum physical extension of the mechanical analogy, a development I will return to in some more detail in the conclusion.43 Before, I would like to turn to my last artefact, that shows how the

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[39] For a more detailed discussion see Arne Schirrmacher: Das leere Atom. Instrumente, Experimente und Vorstellungen zur Atomstruktur um 1903, in: Ulf Hashagen, Oskar Blumtritt, Helmuth Trischler, eds.: Circa 1903: Artefakte in der Gründungszeit des Deutschen Museums, München 2003, 127-152.

[40] Philipp Lenard: Über Kathodenstrahlen. Nobel-Vorlesung, Leipzig 1906, reprinted in Philipp Lenard: Wissenschaftliche Abhandlungen, Vol. 3, Leipzig 1944, 167-197, on 189.

[41] Ibid., a similar passage can already be found some years earlier in Philipp Lenard: Über die lichtelektrische Wirkung, Annalen der Physik 8 (1902), 149-198, on 192.

[42] Cp. the 2003 HSS Annual Meeting contribution of Ruben Martinez: "Plum Pudding and the Folklore of Physics", who demonstrated that the first published account of "plum pudding" came nearly forty years later in a textbook and hence was related to a shift in the manners of physics teaching.

[43] For a detailed account of this development cp. Arne Schirrmacher: Der lange Weg zum neuen Bild des Atoms. Ein Problemfall der Wissenschaftsvermittlung von der Jahrhundertwende bis in die Zeit der Weimarer Republik, in: Sibylla Nikolow/Arne Schirrmacher: Wissenschaft und Öffentlichkeit als Ressourcen füreinander. Wissenschaftshistorische Studien, 1870-1980, in press.

experimental knowledge of the empty atom, even after Rutherford, was rather taken to contradict Bohr's atom than to support it.

From refuting to substantiating the Bohr atom: The Franck-Hertz experiment

As mentioned before, neither the Rutheford atomic model nor Bohr's were an immediate success. Looking through the leading German summary journal that aimed at communicating scientific news between the specialists of different science fields *Die Naturwissenschaften*, for the years between 1913 and 1916 one can find quite a variety of ideas about the atom, however, without any preference to Bohr or Rutherford.[44] Hence, it is no surprise that James Franck and Gustav Hertz started around this time their experimental researches on the atom with Lenard's tubes and methods from his 1902 paper on the photoelectric effect, the very same paper Einstein cited as experimental basis of his 1905 light quanta paper,[45] and they pursued them with the general aim to check "the relations which emerge both from the quantum theory and the considerations of atomic models."[46] Similar to the Debye-Scherrer case, Franck and Hertz knew what they wanted to see: ionization of molecules by bombardment with electrons carrying a certain amount of energy, the so called ionization energy. For this purpose electrons were accelerated by an electric field within a tube which is filled by low-pressure mercury vapor.

Fig. 8: Franck-Hertz tube. LD Didactic GmbH, Produktkatalog Physik, Nr. 555854.

Summarizing their findings, Franck and Hertz, wrote in May 1914 that an energy transfer to the mercury molecules by 4,9 Volt electrons resulted in their ionization.[47] Electrons of less energy showed elastic scattering, those with double the threshold voltage were able to ionize two mercury molecules etc. Implicitly, the authors presupposed that the mercury molecules contain electrons but they did neither assume them to form a specific structure in the atoms nor to have levels of binding to the molecule other than that type that can be destroyed by the ionization process. Like Debye and Scherrer who did not see the electron rings, Franck and Hertz did not see Bohr's energy levels of the atoms.

Bohr, who immediately recognized the support the experiment would lend to his theory, explained in a paper from 1915 that the correct interpretation of the experiment would be to understand the energy threshold as that of the transition between ground state and first exited state of an electron within the mercury atom rather than of ionization which should take place only for much higher voltage. Franck and Hertz, however, did not correct their interpretation but moreover rejected Bohr's view and challenged his whole theory instead.[48]

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[44] For details see ibid.

[45] In James Franck/Gustav Hertz: Über Zusammenstöße zwischen Elektronen und den Molekülen des Quecksilberdampfes und die Ionisierungsspannung desselben, Verh. der Deutschen Physikalischen Gesellschaft 16 (1914), 457-467, they refer to the methods of Lenard, lichtelektrische Wirkung, note 41, as is done in Albert Einstein: Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt, Annalen der Physik 17 (1905), 132-148.

[46] Franck/Hertz, Über Zusammenstöße, note 45, 458.

[47] Ibid., 466.

[48] Niels Bohr: On the quantum theory of radiation and the structure of the atom, Philosophical Magazine 30 (1915), 394-415. James Franck/Gustav Hertz: Über Kinetik von Elektronen und Ionen in Gasen, Physikalische

It took Franck and Hertz some more years to acknowledge that their apparatus did not produce any ionization. Meanwhile the new Bohr-Rutherford atom did find more and more widespread acceptance and the first drawings of it appeared in journals after World War I. and even a wood an metal exhibit were made for the Deutsches Museum.[49]

Fig. 9: Model of the hydrogen atom made for the Deutsches Museum from a concept of Arnold Sommerfeld and artistic advice by the architect Friedrich von Thiersch. Source: DMA, BN 2936.

Apart from arrogating a certain blindness to Franck and Hertz, a closer look at their measurements shows, that contrary to Bohr's predictions of quite a number of transitions between the many energy levels of the atom solely the first one could be seen. Only much later did improved experiments show more structure of the atom. This reminds us of the main characteristic of the looking-into approach that is so clearly represented by the bombardment method: It is very selective of certain properties of matter and does in no way anymore give an account of the whole object under investigation. This selectivity, however, also opens much room for choices of visualizations.

Conclusion: Visibility lost and visualization regained?

In a now classic article of Arthur I. Miller on the genesis of quantum theory, that was expanded in a number of further publications through the last 25 years, the thesis was put forward that around 1913 *visualization* was lost but it was regained around 1927.[50] As this account comports well with the traditional historiography of physical theory development – from Bohr's atom to the Copenhagen interpretation of quantum mechanics – it neither resonates convincingly with the experimental history of physics nor with the history of public communication about advances in this field.[51]

Shifting the point of view to these latter two directions I would like to propose a rather different thesis, which takes much from Luthy's thesis presented in the introduction, and from the two concurrent developments, I discussed, the one of extending visibility and the one of creating new visualizations:

With the new discoveries on radiation and instability of matter in the last decade of the nineteenth century the globular atomic iconography disappeared from the scientific discourse and was at least obscured in the public recognition. While around 1900 the main aspects of the architecture of the modern atom became experimentally known, no new picture of the atom was established until the end of World War I. Hence, we find between 1895 and 1918 a

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Zeitschrift 17 (1916), 409-416, 430-440. For a brief account see John L. Heilbron: Lectures on the history of atomic physics 1900-1922, in: Charles Weiner: History of twentieth century physics, New York 1977, 40-108, on 74-78, more detailed in Giora Hon: Franck and Hertz versus Townsend: A study of two types of experimental error, Historical Studies in the Physical Sciences 20 (1989), 79-106.

[49] Cp. Schirrmacher, Das leere Atom, note 39, 146 ff.

[50] Arthur I. Miller: Visualization lost and regained: The genesis of the quantum theory 1913-1927, in: J. Wechsler, ed: On aesthetics in science, Cambridge Mass. 1978, 73-101, by the same author, e.g., Imagery in scientific thought: Creating twentieth century physics, Boston 1984, and Imagery and representations in Nye, Cambridge History 5, 2003, note 1, 191-215.

[51] Hon, Propagation, note 34, Schirrmacher, Weg, note 43.

period in the history of science devoid of any reasonable atomic iconography. The new picture of the atom became more and more widely used in the following years mostly in the literature aiming at an interested public. In this way the empty planetary atom – as a constructed visualization – became generally accepted just when quantum mechanics disproved the existence of electron orbits.

As it may have become already clear, attempts at explanation of this pictureless period have to go beyond a history of scientific ideas or laboratory work. Also the probably first suggestive model, the Sommerfeld model of 1918, was one created for and with the public. The development may be viewed as a period of multiple superpositions of conflicting developments: Clearly, there was a superposition of attempts to shift the limits of visibility and others to create new types of visualization replacing the visible. But it took place also in Germany, where all four artefacts, which I presented, were employed and the related experimental researches were pursued, and Germany perhaps contributed most to create a new atomic physics. And here we also find a superposition of a well-structured Kaiserreich society with certain expectation with regard to science on the one hand and the emergence of a modern physics leaving behind most of the concepts of classical physics on the other hand, which had, as one may try to argue, a certain relation to or immersion in this particular culture. While, for example, physicists like Max Born and Alfred Landé realized during the 1918 revolution days in Berlin, that not only the political system would change within days, but also the Bohr-Sommerfeld model for the atom cannot live on, since experimental results demonstrated the three-dimensional distribution of electrons in the atom contrary to the planar models, at the same time a disillusioned public was seemingly ready to allow for the lack of solidity and impenetrability of matter and to accept just this new picture presented in various articles in popular science journals through the 1920s.[52]

These remarks may suffice to show how complex this particular episode in the history of science actually becomes, when freed from the pure internalistic perspective. Since it is here not the place to tell this story more fully, I would like to conclude my paper with three points on physics, artefacts and museums.

1) As Giora Hon has argued convincingly, the progress quantum theory made in explaining the atom in the first two decades of the twentieth century were only possible when propagation experiments like the researches on black-body radiation and spectroscopy were combined with bombardment experiments like those of Lenard, Rutherford and Franck and Hertz.[53] In this article I argued that this development is also mirrored in the disappearance and later in the establishing or a new atomic iconography. In writing a history of physics we should therefore not deny the existence of this transitory period of ambiguity and superposition of different, at times contradictory experimental and theoretical approaches and findings. In this way also the projects of pushing the limits of visibility and of creating new way of visualization were concurrent parts of this development, both necessary to give rise to modern atomic physics.

2) The key to illuminating the process of establishing new theories, new models and new images in science lies in the artefacts. Microscopes and discharge tubes bridge the fractures in interpretation, theory and iconography. It is probably worthwhile to rank higher the "Atomphotogramme", Laue spot photographs or ultramicroscopic pictures as compared to the

[52] Letter Max Born to David Hilbert, 14. Nov. 1918, Hilbert papers, Staats- und Universitätsbibliothek Göttingen, box. 40A, Nr. 18; Schirrmacher, Weg, note 43.

[53] Hon, Propagation, note 34, 168f.

often retrospectively constructed plum-pudding models, electron rings or particle accelerator events on the computer screen. Examples like the Debye-Scherrer camera or the Lenard tube show that telling the stories of artefacts exhibit a great extent of autonomy, that can be distinguished from those of theory and imagery.

3) It should be a special challenge, and probably also a definite chance, for science museums to communicate also ambiguous scientific times like the pictureless periods of the atom. But can one build a physics exhibit about the emerging quantum theory (or ancient atomism) without the typical images? At least, I would argue, one should start telling the histories of the main experiments that led to modern atomic physics without squinting at school textbooks, infallibility of scientific heroes or straightforwardness of scientific progress.

If the there is a field where the slogan "visibility lost and visualization regained" is to be read as a warning, then probably in the science museum: We should rather try to extend the visibility – in particular of artefacts – in the museum, rather than to content ourselves with finding selective and at times manipulating visualizations.

Figures

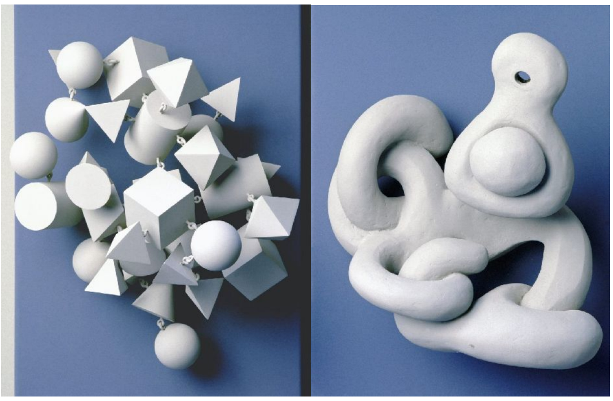

Fig. 1 a) and b)

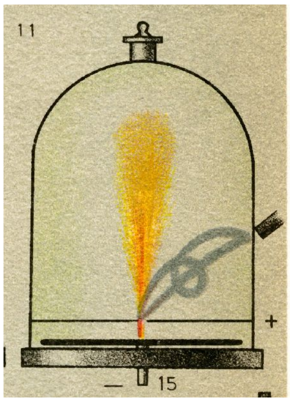

Fig. 2

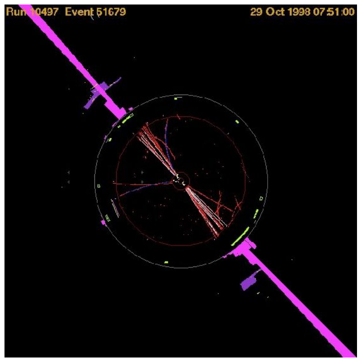

Fig. 3

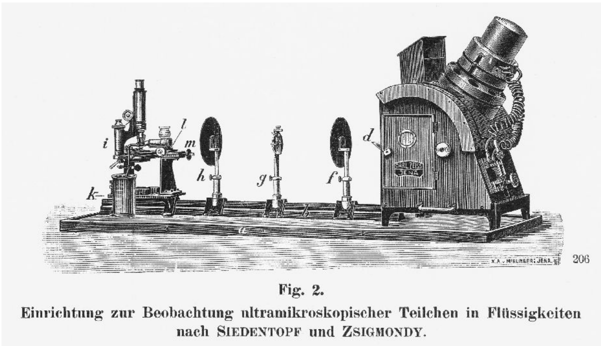

Fig. 4

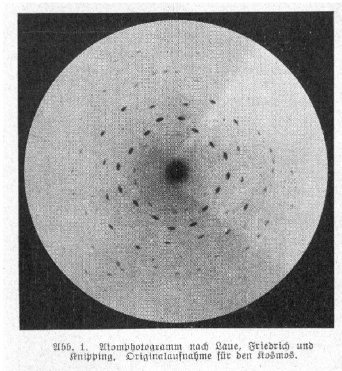

Fig. 5 a)

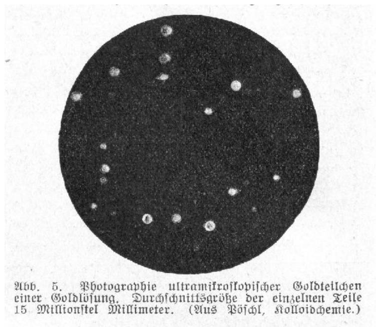

Fig. 5 b)

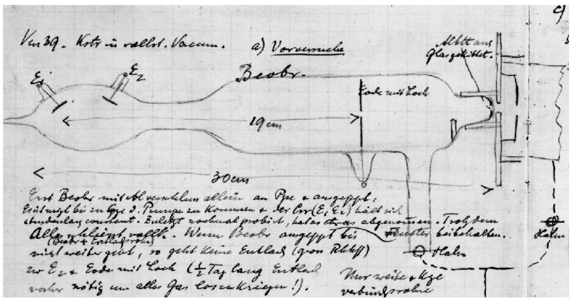

Fig. 7 a)

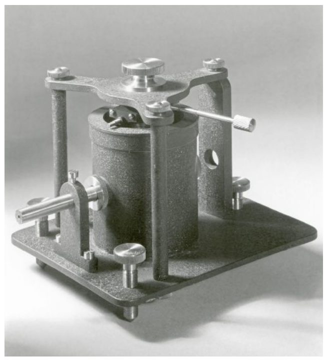

Fig. 6

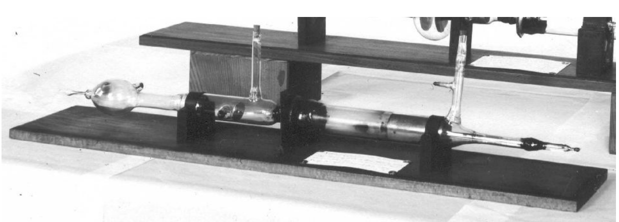

Fig. 7 b)

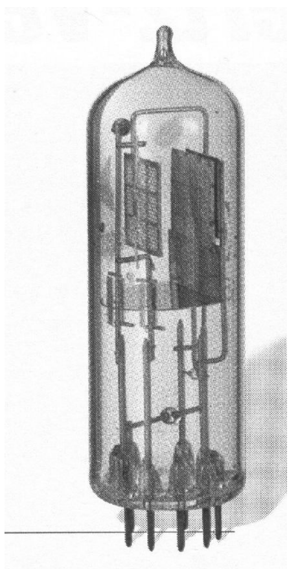

Fig. 8)

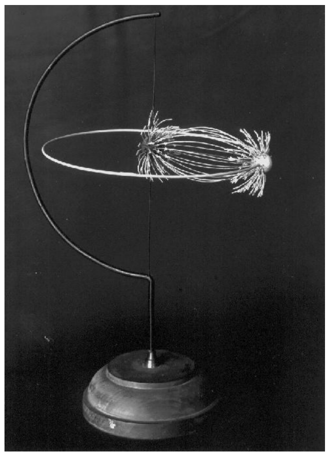

Fig. 9)