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Early Seventeenth-Century Atomism

Theory, Epistemology, and the Insufficiency of Experiment

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DURING THE SCIENTIFIC REVOLUTION two relatively independent developments joined forces: the mechanization of the world picture, to use Anneliese Maier's famous term, and the recognition of the crucial role to be played by observation and experiment in the establishment of a scientifically valid theory. The attempt to describe natural phenomena by means of particles and motion was appealing to the new scientific age. Within a few decades corpuscular theories of matter evolved from the obliquity of a controversial fancy into a widely accepted rationale. Compared, however, to the rise of astronomy and mechanics, this success remained ambiguous. Seventeenth-century atomism did not necessarily provide fertile soil for an understanding of material properties and processes. Its empirical background was weak, and not one of its alleged proofs would be accepted by today's scientific standards. In Galileo's inclined plane and his law of falling bodies, or in Newton's theory of colors and his *experimentum crucis* with the prism, theory and experiment, observation and conclusion, were connected in a way that is still convincing. In atomism, however, there was no experimental proof possible, although most corpuscular theories of the seventeenth century explicitly claimed to be based upon experience. But it was not until the nineteenth century that experimental results made the atomic theory at least plausible.

The questionable relationship between seventeenth-century atomism and its empirical background has been obscured to some extent by later historians. When the standard histories of atomism were written, the atomic hypothesis itself was still very much under debate. Twentieth-century historians of science, on the other hand, have all too easily taken the atom for granted. With few exceptions they dealt with these issues in terms of mere intellectual history and neglected the empirical aspects or underestimated their importance. In 1968 Hans Kangro reminded us that the empirical difficulties involved in early modern corpuscularianism are well worth being studied by historians of science.[1]

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[1] Hans Kangro, "Erklärungswert und Schwierigkeiten der Atomhypothese und ihrer Anwendung auf chemische Probleme in der ersten Hälfte des 17. Jahrhunderts," *Technikgeschichte*, 1968, *35*:14–

In this article I give a historical typology and evaluation of the arguments presented in support of the corpuscular hypothesis during the first half of the seventeenth century. I intend to focus on authors who considered themselves empiricists; in their systems the clearest departure from merely bookish reasoning should be expected. Nevertheless, the empirical approach was embedded in a whole network of ontological, epistemological, and mathematical arguments. Such arguments created patterns of thought and habits of perception that were instrumental in the acceptance of the corpuscular view.

I. PARTICLES: PRESUPPOSITION OR PROOF?

Early in the seventeenth century, the assumption of the existence of atoms was by no means a scientific hypothesis that could be proposed without extensive justification of its empirical validity, philosophical soundness, and religious acceptability. One does not even need to go as far as Pietro Redondi in his recent *Galileo eretico* to see that atomism was a most dangerous topic indeed.[2] Its experimental confirmation would have been extremely momentous, not only for the theory of matter.

In 1624 Jean Bitaud and Antoine de Villon, two otherwise unknown Parisian scholars, announced a public tribunal directed against the doctrines of Aristotle and Paracelsus. They were assisted by Etienne de Clave, a physician and skilled chemist, who was scheduled to prove the truth of the assertions by public experiments. The theses the three authors prepared for this event were aimed at disproving the Peripatetic assumptions about matter and form, and the Paracelsian *tria prima*. They culminated in the fourteenth thesis in a clear commitment to atomism: "Omnia . . . esse in omnibus, et omnia componi ex Atomis seu indivisibilibus. Quod utrumque, quia rationi, verae philosophiae, et corporum anatomiae conforme est, mordicùs defendimus, et intrepidi sustinemus." The reaction of the authorities was surprisingly vigorous. Not only was the assembly that had gathered for the event dissolved, one of the organizers arrested, and the theses torn up, but it was also forbidden to propagate anything of this nature under penalty of death.[3] It remains unclear whether the authorities intervened because

36. For nineteenth-century histories see, e.g., Friedrich Albert Lange, *Geschichte des Materialismus und Kritik seiner Bedeutung in der Gegenwart*, ed. Alfred Schmidt (1866; 2nd ed., 1872; Frankfurt: Suhrkamp, 1974); Kurd Lasswitz, *Geschichte der Atomistik vom Mittelalter bis Newton*, 2 vols. (Hamburg/Leipzig, 1890); and Richard Ehrenfeld, *Grundriß einer Entwicklungsgeschichte der chemischen Atomistik* (Heidelberg: Winter, 1906). For exceptions to the rule for twentieth-century histories see Ernst Bloch, "Die antike Atomistik in der neueren Geschichte der Chemie," *Isis*, 1913, *1*:377–415; J. R. Partington, "The Origins of the Atomic Theory," *Annals of Science*, 1939, *4*:245–282; and R. Hooykaas, "The Experimental Origin of Chemical Atomic and Molecular Theory before Boyle," *Chymia*, 1949, *2*:65–80. For standard twentieth-century histories see Hélène Metzger, *Les doctrines chimiques en France du début du XVIIe à la fin du XVIIIe siècle* (1923; Paris: Blanchard, 1969); G. B. Stones, "The Atomic View of Matter in the XVth, XVIth, and XVIIth Centuries," *Isis*, 1928, *10*:445–465; Marie Boas, "The Establishment of the Mechanical Philosophy," *Osiris*, 1952, *10*:412–541; and Stephen Toulmin and June Goodfield, *The Architecture of Matter* (1962; Chicago/London: Univ. Chicago Press, 1982), pp. 137–200. For a purely semantic and philosophical treatment see Ugo Baldini, "Il corpuscolarismo italiano del Seicento: Problemi di metodo e prospettive di ricerca," in *Ricerche sull'atomismo del Seicento* (Pubblicazioni del Centro di Studi del Pensiero Filosofico del Cinquecento e del Seicento in Relazione ai Problemi della Scienza, I, 9) (Florence: Nuova Italia, 1977), pp. 1–76.

[2] Pietro Redondi, *Galileo eretico* (Microstorie, 7) (Turin: Einaudi, 1983).

[3] *Positiones publicae contra dogmata Aristotelica, Paracelsica, et Cabalistica,* thesis 14. The "omnia in omnibus" refers to the three authors' peculiar doctrine of five elements. The quotation is

an atomic theory of matter seemed to question the transubstantiation of the Eucharist. We are more concerned with the assertion, proposed by the authors, that the atomic doctrine was not only reasonable but also in accordance with chemical analysis (*corporum anatomiae conforme*) and that there were experiments or observations that would immediately decide between the competing hypotheses about the nature of matter and thus convince everybody: "Experientijs atque iteratis rationibus ita sua dicta comprobet, omniumque oculis tam apertè subjicitat, ut omnes adstantes verissima haec omnia uno simul ore fatentur."[4]

When Robert Boyle, only a generation later, began to establish his corpuscular philosophy, a mechanical theory of matter based exclusively upon the two principles "matter" and "motion," he did not dwell on the trifling task of proving the existence of atoms or corpuscles first. Instead, he presupposed them and developed his hypothesis to direct and explain the experimental operations based on it. Although Boyle admitted that there was little systematic connection between empirical facts and the corpuscular hypothesis, the operational, if not ontological, status of the corpuscles was beyond any doubt.[5] In the *Sceptical Chymist,* published in 1661, he devoted much effort to criticizing and refuting experimentally the doctrines of elements or principles proposed by the Peripatetics and Paracelsians, yet his own corpuscular alternatives were never exposed to the touchstone of the experiment.

II. THE RISE OF ATOMISM

The knowledge of classical atomism had been passed down to the Renaissance humanists through different lines of tradition. Above all, there was Aristotle's consistent refutation of it, which became an integral part of every scholar's training in philosophy. Second, the writings of Greek medicine incorporated important relics of atomism. Besides these, the doctrine of *minima naturalia,* as put forth in the Averroist tradition of commentators and more fully developed in the sixteenth century, provided a concept of small, qualitatively different parts of matter that related more closely to experience than did the atoms of the ancients.[6] The *minima,* however, were not mechanical particles and could not sim-

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taken from an early reprint in the anonymously edited *Auctarium epitomes physicae . . . Danielis Sennerti* (Hamburg, 1635), pp. 86–91, a collection of short texts, mainly from Sennert's *Epitome scientiae naturalis*. It is clear that the Hamburg edition was commissioned by Joachim Jungius, who was also responsible for the addition of the *Positiones*. The main sources for the incident are Jean Baptiste Morin, *Réfutation des thèses erronées* (Paris, 1624); and Marin Mersenne, *La vérité des sciences contre les s[c]eptiques ou Pyrrhoniens* (Paris, 1625), pp. 78–83; see also Lynn Thorndike, *A History of Magic and Experimental Science,* Vol. VII: *The Seventeenth Century* (New York: Columbia Univ. Press, 1958), pp. 186–187.

[4] *Positiones publicae* (cit. n. 3), p. 91. In the only surviving original broadsheet (Bibliothèque Nationale, Paris, MS Dupuy 630, fol. 72) this passage is wanting, but a manuscript copy (Biblioteca Apostolica Vaticana, MS Reg. lat. 952, fols. 47–48v) confirms the quoted version.

[5] See Thomas S. Kuhn, "Robert Boyle and Structural Chemistry in the Seventeenth Century," *Isis,* 1952, *43*:12–36; and William Arthur Drumin, "The Corpuscular Philosophy of Robert Boyle: Its Establishment and Verification" (Ph.D. diss., Columbia Univ., 1973), esp. pp. 120–149.

[6] Alfred Stückelberger, *Vestigia Democritea: Die Rezeption der Lehre von den Atomen in der antiken Naturwissenschaft und Medizin* (Schweizerische Beiträge zur Altertumswissenschaft, 17) (Basel: Reinhardt, 1984); Stückelberger, "Empirische Ansätze in der antiken Atomphysik," *Archiv für Kulturgeschichte,* 1974, *56*:124–140; and Stückelberger, *Antike Atomphysik: Texte zur antiken Atomlehre und ihrer Wiederaufnahme in der Neuzeit* (Munich: Heimeran, 1979), pp. 33–38. Still the best account of the medieval doctrine of *minima naturalia* with regard to atomism is A. G. M. van Melsen, *From Atomos to Atom: The History of the Concept Atom* (Pittsburgh: Duquesne Univ.

ply be translated into corpuscular terms. Therefore, additional factors are necessary to account for the sudden rise and reluctant acceptance of atomism in the first half of the seventeenth century, just as the attractiveness of Aristotelianism was fading away. When in 1417 the lost *De rerum natura* by Lucretius, with its wealth of immediately convincing imagery, was rediscovered, it provided the proper impulse at the very best moment. The *editio princeps* appeared in 1473, only three years after the first Latin translation of Diogenes Laertius's biographical history of philosophy, the last two books of which dealt with Leucippus, Democritus, and Epicurus. Still, it was some time before its influence became evident in the natural sciences. The Italian physician Girolamo Fracastoro, in his *De sympathia et antipathia rerum* of 1545, was probably the first of the humanists to use the ancient atomic theory in explaining physical and chemical phenomena. In the following decades Hero's *Pneumatica*, another influential source for Greek atomism, went through many translations into Latin and the vernacular.[7] At the turn of the seventeenth century the debate between supporters and adversaries of the atomic doctrine had stimulated enough interest to encourage deliberate experimentation.

By that time internal problems within the Scholastic framework had weakened the Aristotelian position. One of these problems was the assumption of a *creatio ex nihilo* of substantial forms. On the basis of the eternity and uncreatedness of Being, Aristotle had assumed that in many alterations, especially when elements were transmuted or new compounds formed, the form of the product appeared out of nothing, *ex nihilo*, whereas the forms of the original bodies disappeared into nothing, *in nihilum*. This issue had been vigorously disputed by the Peripatetics ever since. In Averroes' opinion forms were merely subordinate to matter and appear from or disappear into matter, and not from or into nothing. The later Averroism, as it flourished in the School of Padua in the sixteenth century, taught that during the process of mixture the forms were only broken (*refractae*) or gradually weakened. The followers of Avicenna, on the other hand, were inclined to admit the persistence of substantial forms of the reactants in a compound, although dominated by the more powerful substantial form of the mixture. It was exactly the latter view, that a compound contained its elements *in actu*, which was favored among the Peripatetic physicians, and it was but natural that Avicenna's doctrine made people more inclined to accept unchangeable and enduring corpuscles as constituent parts of a mixture.[8] The Lucretian axiom *nihil ex nihilo*, echoing Epicurus, must have been appealing as a simple and reasonable way out of the dilemma. In addition, the axiom was also not unacceptable to an enlightened, "secular" Aristotelianism, despite the theological difficulties that arose if *nihil ex nihilo* was confronted with the biblical account of creation.[9]

Press, 1952). I use the enhanced German translation *Atom gestern und heute: Die Geschichte des Atombegriffs von der Antike bis zur Gegenwart* (Orbis Academicus, II, 10) (Freiburg/Munich: Alber, 1957).

[7] Wilhelm Schmidt, "Heron von Alexandria im 17. Jahrhundert," *Abhandlungen zur Geschichte der Mathematik*, 1898, *8*:195–214; and Marie Boas, "Hero's 'Pneumatica': A Study of Its Transmission and Influence," *Isis*, 1949, *40*:38–48.

[8] See W. Subow, "Zur Geschichte des Kampfes zwischen dem Atomismus und dem Aristotelismus im 17. Jahrhundert (Minima naturalia und Mixtio)," in *Sowjetische Beiträge zur Geschichte der Naturwissenschaft*, ed. Gerhard Harig (Berlin: Deutscher Verlag der Wissenschaften, 1960), pp. 161–191; Norma E. Emerton, *The Scientific Reinterpretation of Form* (Cornell History of Science Series) (Ithaca/London: Cornell Univ. Press, 1984), pp. 76–105.

[9] Lucretius, *De rerum natura* 1.150 ("nullam rem e nihilo gigni"), 1.215 ("natura neque ad nihilum

Influenced by nominalist thought, many natural philosophers turned toward the empirically accessible particulars of nature. In David Gorlaeus's posthumously published *Exercitationes philosophicae* of 1620 universals had no existence; only individual things, defined by their intrinsic properties, were real: that is, essence and existence, essence and properties, quantity and body, were the same.[10] Only in thought could the attributes of a body, such as number, quantity, and physicochemical properties, be distinguished from the body itself. The only reality was the reality of the physical particulars, the atoms: *nihil reale esse in corporibus praeter atomos*. Occam's razor, that the entities are not to be multiplied beyond necessity, was quoted by Gorlaeus again and again. A decade later Joachim Jungius referred to it as the *hypothesis hypotheseon*.[11]

The experience of practical men, separated from the mainstream of learning by educational and social barriers, had become more influential since the Renaissance. By the very nature of their crafts they treated matter in a nonphilosophical, purposeful way. For obvious reasons metallurgists, assayers, chemists, and apothecaries were more concerned with the properties of the products than with the theory of the processes. Seventeenth-century chemistry was a rational and pragmatic subject, devoted to medical, pharmaceutical, and metallurgical purposes.[12] If we judge it on the basis of Jean Beguin's *Tyrocinium chymicum* of 1610, the most influential chemical manual of the time, the field had divorced itself from the old dream of gold and longevity and was explicitly atheoretical and concerned primarily with substances, their essentials, and their classification as distinct species. It should also be remembered that the available theories of matter rested upon a rather limited acquaintance with metals and minerals. Alchemists and practical men, on the other hand, knew a great deal about these things, and they knew how to handle and study them experimentally. As far as the experimental approach is concerned, the alchemical heritage did much to determine the questions of early modern theory of matter. Within this context of empirical chemistry the corpuscular hypothesis gained momentum and made converts. If we examine the web of arguments presented in support of the atomic theory of matter during the first half of the seventeenth century, the chemical arguments appear particularly powerful.

III. EPISTEMOLOGICAL ARGUMENTS

Many of the arguments adduced in support of atomism were epistemological. Of these, one important group was concerned primarily with the relationship be-

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interemat res"), et passim; Epicurus *apud* Diogenes Laertius 10.38–39. On secular Aristotelianism see John Henry, "Thomas Harriot and Atomism: A Reappraisal," *History of Science*, 1982, *20*:267–296, on p. 272.

[10] David Gorlaeus, *Exercitationes philosophicae quibus universa fere discutitur philosophia theoretica* (Leiden, 1620), pp. 39–40, 84–85, 95–100. See also Lasswitz, *Geschichte der Atomistik* (cit. n. 1), Vol. I, pp. 455–463; and esp. Tullio Gregory, "Studi sull'atomismo del Seicento, II: David van Goorle e Daniel Sennert," *Giornale critico della Filosofia Italiana*, 1966, *45*:44–63, on pp. 46–51.

[11] Gorlaeus, *Exercitationes philosophicae* (cit. n. 10), pp. 39, 95–96 (on distinguishing attributes; see also Gregory, "Studi sull'atomismo, II," cit. n. 10, pp. 46–48); and p. 247 (on reality; see also Gorlaeus, *Idea physicae* [Utrecht, 1651], pp. 24–25); and Joachim Jungius, *Praelectiones physicae*, ed. Christoph Meinel (Veröffentlichung der Joachim-Jungius-Gesellschaft der Wissenschaften, 45) (Göttingen: Vandenhoeck & Ruprecht, 1982), p. 96, lines 1–10.

[12] Marie Boas, *Robert Boyle and Seventeenth-Century Chemistry* (Cambridge: Cambridge Univ. Press, 1958), pp. 48–74.

tween the structures of the external world and the corresponding structures and abilities of human perception and cognition. In regard to that relationship, one solution, rigid mechanical atomism, had little to offer the more empirically minded naturalists. Since it located the observed qualities within the sensations and the mind of the observer, how could one ever be able to know about reality through experiment? A solution at the other extreme was proposed by Claude Gillermet de Bérigard, a Frenchman who taught in Pisa and Padua, knew Galileo personally, and is likely to have witnessed the condemnation of the atomistic *Positiones publicae* at Paris in 1624. In his *Circulus Pisanus* of 1643, a rather traditional dialogue, Bérigard suggested a theory of matter that might be termed a "qualitative atomism."[13] Every possible quality was, so to speak, incorporated into atoms, each atom being the corporeal hypostasis of only one quality. Consequently, there were as many different kinds of atoms as there were different qualities in nature, and only their juxtaposition and interference in macroscopic aggregates added up to the qualities we see, feel, smell, or taste. The remarkable point in Bérigard's theory is that his quality-atoms were unchangeable, so that qualities became the basic entities in nature, and the study of qualities, as it could be performed in the laboratory, would eventually lead to the basic level of reality. Thus Bérigard was able to avoid the epistemological break between the sensuous qualities and the properties of the atoms which had been such a disturbing feature of Greek atomism.[14]

Usually, however, the solution to this problem of how the primary qualities of the corpuscles produce the sensation of secondary qualities in the observer was sought somewhere between the two extremes. Thus the notion of element—and this means of course the four Aristotelian elements—was to some extent amalgamated with that of atoms. The identification of corpuscles and elements is already present in Sebastian Basso's *Philosophia naturalis adversus Aristotelem* of 1621. The author admitted, however, that it would be impossible to decide whether the particles of fire, air, water, and earth were in fact the ultimate atoms, and so he was probably the first to introduce a clear concept of secondary, tertiary, quaternary, and so on, aggregates which, in chemical reactions, behave as if they were stable particles.[15] In a similar way Daniel Sennert, a very influential yet little-studied figure, imagined the *minima naturae* or *atomi* to be smallest units of the four elements, which in turn compose the *prima mixta* as the real, experimentally treatable units of matter. The closest amalgamation of the concepts of atom, element, and pure substance that can be found before the nineteenth century, however, was reached by Joachim Jungius in 1632.[16] Here

[13] Claudius Berigardus, *Circulus Pisanus de veteri et peripatetica philosophia* (1643; Padua, 1661), pp. 418–425.

[14] Jürgen Mau, "Studien zur erkenntnistheoretischen Grundlage der Atomlehre im Altertum," *Wissenschaftliche Zeitschrift der Humboldt-Universität zu Berlin* (Gesellschafts- und sprachwissenschaftliche Reihe, 2, 3), 1952/53, pp. 1–20.

[15] Reijer Hooijkaas, *Het Begrip Element in zijn historisch-wijsbegeerige Ontwikkeling* (Utrecht: Schotanus & Jens, 1933), pp. 136–143, 183–190; see also Henricus Hermanus Kubbinga, "Le développement historique du concept de 'molécule' dans les sciences de la nature jusqu'à la fin du XVIIIe siècle" (diss., Ecole des Hautes Etudes en Sciences Sociales, Paris, 1983), pp. 60–73.

[16] Rembert Ramsauer, "Die Atomistik des Daniel Sennert als Ansatz zu einer deutschartigschauenden Naturforschung und Theorie der Materie im 17. Jahrhundert" (Ph.D. diss., Univ. Kiel, 1935), is the only full-length, if ideologically biased, study of Sennert's corpuscular theory. For Sennert's achievements see J. R. Partington, *A History of Chemistry*, Vol. II (London: Macmillan, 1961), pp. 271–276; for his "chemical" theory see Gregory, "Studi sull'atomismo, II" (cit. n. 10), pp.

the gap between perceivable and experimentally accessible qualities of macroscopic bodies and those of the ultimate constituents of matter had almost disappeared.

Another epistemological assumption underlying atomism was that knowledge requires the existence of some basic entities in reality upon which, as upon irreducible units or axioms, both cognition and the plurality of nature could be built. It was no less a person than Giordano Bruno who incorporated this idea—originally formulated by Nicholas of Cusa—into his notion of *minimum*. For Bruno, the existence of a smallest, indivisible unit, such as the point in geometry, the atom in physics, and the monad in metaphysics, was the matrix of reality, the measure and prerequisite of cognition.[17] However, Bruno's physical atoms had no sensuous properties, they were all of the same kind, and only in the senses did they appear endowed with specificity. But still they were the units out of which nature builds her fabric and into which bodies dissolve again.[18] Since the same principle of synthesis and analysis was valid in art and in nature, it should be not only natural but indeed necessary to proceed from the simple to the complex, once the point of departure had been found.

In 1621 Sebastian Basso, one of the most influential authors among the early corpuscularians, proposed the argument that the instauration of learning had to begin with the most basic entities of reality, namely, the physical principles or atoms, from which level all future conclusions would depend. Their exact determination would be a prerequisite for any solid science, since these principles were as important in the natural sciences as characters in typography or building materials in a construction. Consequently, they had to be preexistent, incorruptible, and finite in number.[19] Jungius's thoughts were quite similar. In his opinion a distinct science of nature required above all a finite number of principles, just as Euclidean geometry relies upon a small number of basic entities such as the point, the line, and the angle. Jungius's attempt to rebuild the system of physical knowledge belongs to the widespread quest for making both philosophy and natural science as axiomatically structured as geometry. In contrast to most of his contemporaries, Jungius insisted that only the evidence of sensuous experience and an inductive methodology would lead to the identification of these ultimate units of reality. These *hypostatical principles,* as he termed them, were not me-

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51–63. On Jungius see Christoph Meinel, "Der Begriff des chemischen Elementes bei Joachim Jungius," *Sudhoffs Archiv,* 1982, *66*:313–338, on p. 336.

[17] On Nicholas see Werner Schulze, *Zahl, Proportion, Analogie: Eine Untersuchung zur Metaphysik und Wissenschaftshaltung des Nikolaus von Kues* (Buchreihe der Cusanus-Gesellschaft, 7) (Münster: Aschendorff, 1978); and Fritz Nagel, *Nicolaus Cusanus und die Entstehung der exakten Wissenschaften* (Buchreihe der Cusanus-Gesellschaft, 9) (Münster: Aschendorff, 1984). For Bruno's theory of matter see Paul-Henri Michel, "L'atomisme de Giordano Bruno," in *La science au seizième siècle* (Histoire de la pensée, 2) (Paris: Hermann, 1960), pp. 249–264; and Michel, "Les notions de continu et de discontinu dans les systèmes physiques de Bruno et de Galilée," in *L'aventure de l'esprit* (Mélanges Alexandre Koyré, 2) (Paris: Hermann, 1964), pp. 346–359.

[18] Iordanus Bruno, *De triplici minimo et mensura* (1591), in *Iordani Bruni Nolani Opera latine conscripta,* ed. F. Tocco and H. Vitelli, Vol. I, Pt. 3 (Florence, 1889; Stuttgart/Bad Cannstadt: Frommann Holzboog, 1962), pp. 139–140.

[19] Sebastianus Basso, *Philosophiae naturalis adversus Aristotelem libri XII, in quibus abstrusa veterum physiologia restauratur et Aristotelis errores solidis rationibus refelluntur* (1621; Amsterdam, 1649), here on p. 8. On Basso and his influence see Tullio Gregory, "Studi sull'atomismo del Seicento, I: Sebastiano Basso," *G. Critico Fil. Ital.,* 1964, *43*:38–65, esp. pp. 49–50; and Giancarlo Zanier, "Il macrocosmo corpuscolaristico di Sebastiano Basso," in *Richerche sull'atomismo* (cit. n. 1), pp. 77–118.

chanical atoms in the classical or in the Boylean sense, but real, chemically distinct parts that could be separated by chemical analysis.[20]

IV. ARGUMENTS BASED ON DIVISIBILITY

The second type of argument for or against atomism was based on mathematical or geometrical grounds. The ancient refutation of atomism had been based upon reasoning of this kind, since logical contradictions result if one assumes that division of continuous bodies leads to indivisible bodies, or, vice versa, that geometrical points add up to form an extended line. It was the concept of the atom as the limit of divisibility that dominated philosophical discussion from Aristotle to the Renaissance, and the arguments need not be repeated here. Their impact was still felt in the seventeenth century, for instance, in Galileo's theory of matter or in Thomas Harriot's unpublished notes on Zeno's paradoxes, in which Harriot inferred the atoms on the basis of mathematical progressions, which he considered as analogues to the structures of the corporeal world.[21] In general, however, it was more the concept of a physical atom as a constituent part that became the prevailing idea at this time. Thus the *ἄτομος* was replaced by the concept of principle (*ἀρχή*) or element (*στοιχεῖον*)—although "element" was intended in a formal, not in any chemical, sense as a binary relation in the form "x is an element of y" that goes back to the Aristotelian definition. For Giordano Bruno the *minimum* was clearly a relational notion that referred to the process of composing and decomposing, an idea that allowed him to distinguish mathematical and physical *minima,* at the price, however, of somewhat bizarre mathematics.[22] Yet for those who professed themselves empiricists the mathematical arguments had little to do with their scientific questions. They reluctantly dismissed the quarrel about the difference between atoms and limits in favor of a more pragmatic concept of little particles that looked as if it would be useful in the laboratory. This change of attitude is best illustrated by Sennert's dismissal

[20] Hans Kangro, *Joachim Jungius' Experimente und Gedanken zur Begründung der Chemie als Wissenschaft: Ein Beitrag zur Geistesgeschichte des 17. Jahrhunderts* (Boethius, 7) (Wiesbaden: F. Steiner, 1968), pp. 194–211; and Meinel, "Begriff des chemischen Elementes" (cit. n. 16). See also Christoph Meinel, *In physicis futurum saeculum respicio: Joachim Jungius und die Naturwissenschaftliche Revolution des 17. Jahrhunderts* (Veröffentlichung der Joachim-Jungius-Gesellschaft der Wissenschaften, 53) (Göttingen: Vandenhoeck & Ruprecht, 1984); and, on the quest for axiomatic structure, Hermann Schüling, *Die Geschichte der axiomatischen Methode im 16. und 17. Jahrhundert* (Studien und Materialien zur Geschichte der Philosophie, 13) (Hildesheim/New York: Olms, 1969), pp. 72–75.

[21] For Galileo's theory of matter see William R. Shea, "Galileo's Atomic Hypothesis," *Ambix,* 1970, *17*:13–27; A. Mark Smith, "Galileo's Theory of Indivisibles: Revolution or Compromise?" *Journal of the History of Ideas,* 1976, *37*:571–588; and Homer E. Le Grand, "Galileo's Matter Theory," in *New Perspectives on Galileo,* ed. Robert E. Butts and Joseph C. Pitt (The University of Western Ontario Series in Philosophy of Science, 14) (Dordrecht/Boston: Reidel, 1978), pp. 197–208. On Harriot see Henry, "Thomas Harriot" (cit. n. 9), pp. 269–271. On ancient refutations of atomism see S. Luria, "Die Infinitesimaltheorie der antiken Atomisten," *Quellen und Studien zur Geschichte der Mathematik, Astronomie und Physik,* Ser. B, 1932, *2*:106–185; and Jürgen Mau, *Zum Problem des Infinitesimalen bei den antiken Atomisten* (Deutsche Akademie der Wissenschaften zu Berlin, Institut für hellenistisch-römische Philosophie, Veröffentlichung 4) (Berlin: Akademie-Verlag, 1954), pp. 19–47.

[22] For Aristotle see Aristotle, *Physics* 1.2 (185a4); for Bruno see Lasswitz, *Geschichte der Atomistik* (cit. n. 1), Vol. I, p. 377. In *Metaphysics* 6.3 (1014b5) Aristotle used the term *element* (*στοιχεῖον*) metaphorically to denote any small, simple, and indivisible unit. In the seventeenth century this inconsistency was seen as a justification for the attempt to harmonize the Aristotelian and Democritean views of matter.

of mathematical arguments in matter theory. In the concluding paragraph of his chapter on atoms in the *Hypomnemata physica* he frankly declared that in physics the divisibility of the continuum was not a relevant question. The only relevant question was whether nature in generation and resolution subsists in some kind of small bodies.[23]

V. ARGUMENTS BASED ON EXPERIENCE AND EXPERIMENTS

The empirical arguments presented in favor of atomism during the first half of the seventeenth century fall roughly into six groups:

1. Extrapolations from the visible to beyond the limits of sense perception.
2. Attempts to use the microscope to extend the reach of the eyes to the intrinsic textures of matter.
3. Transport processes of material character, such as evaporation, abrasion, or growth.
4. Arguments taking the physical problems related to condensation and rarefaction, including the question of the vacuum, as their point of departure.
5. Observations related to noncorporeal species such as light, magnetism, sound, or heat.
6. Arguments derived from phenomena involving qualitative alterations of chemical substances.

Extrapolations

Arguments based upon extrapolations from macroscopic bodies were the more traditional ones, already put forward in classical antiquity; most of them in fact are in Lucretius's *De rerum natura*. They all start from the trivial experience that macroscopic bodies are distinct and go on to extrapolate from this distinctiveness to an underlying material reality. The most frequently quoted example was the one of insects that are so tiny that their third part would be below the limits of visibility. How small then, Lucretius asked, must their internal organs be, how small their heart, their eyes, their feet? And each of these is in turn composed of atoms. Although Lucretius's consideration was aimed merely at making plausible the unbelievably small size of atoms, the observation was frequently quoted in order to prove their very existence. It occurs in Bruno, Basso, Sennert, Gassendi, and Magnenus, to mention only a few.[24] On a similar level lies Lucretius's comparison of the atomic size with the size of the tiny motes dancing back and forth if a ray of sunlight falls in a dark room. Again the passage, which goes back

[23] Daniel Sennertus, *Hypomnemata physica* (1636), in *Danielis Sennerti Opera omnia,* 4 vols. (Lyons, 1656), Vol. I, pp. 100–172, *Hypomnema* 3.1.1: "De atomis et mistione," p. 119. See also Sennertus, *De consensu et dissensu Galenicorum et Peripateticorum cum Chymicis* (1619), in *Opera,*Vol. I, pp. 177–284, here Ch. 12, p. 230.

[24] Lucretius, *De rerum natura* 4.116–122; cf. Bruno, *De triplici minimo* (cit. n. 18), 1.9.12–20, p. 169; Basso, *Philosophia naturalis* (cit. n. 19), p. 15; Sennertus, *Hypomnema* 3.1.1, p. 119; Petrus Gassendi, *Animadversiones in decimum librum Diogenis Laertii, qui est de vita, moribus, placitisque Epicuri,* 2 vols. (Lyons, 1649), Vol. I, p. 221, also in Gassendi, *Syntagma philosophicum* 2.1.3, in *Petri Gassendi Opera omnia in sex tomos divisa,* 6 vols. (Lyons, 1658), Vol. I, p. 269; and Iohannes Chrysostomus Magnenus, *Democritus reviviscens sive vita et philosophia Democriti* (Leiden, 1648), p. 206.

to Democritus, was referred to by Basso, Gassendi, and many others in the seventeenth century.[25] Evidently most of these references, even if they did not always mention their sources, go back to classical authorities, not to fresh observation. The empirical facts referred to were *topoi* of the scholarly literature. Their aim was to appeal to the reader's erudition and imagination, rather than to his critical or experimental abilities. They belong to a literary tradition of figurative rhetoric, aimed at creating astonishment and, by means of astonishment, assent and persuasion. Their frequent occurrence reflects once more the overwhelming influence of Lucretius's *De rerum natura* upon sixteenth- and seventeenth-century minds, not only because of its scientific merits, but also because of its poetic and imaginative qualities.[26]

Authors only scarcely expanded on these examples; instead they simply repeated or quoted them either in action or in writing. Bérigard presents us with a carefully designed experimental verification of Lucretius's motes in the sunbeam. His aim was to exclude the possibility that the phenomenon might be caused by major particles such as normal dust. For this purpose he sealed a glass vessel and kept it quiet for a very long time to make sure that all dust had settled down. The minute reflecting particles he was nevertheless able to see inside the glass were therefore judged to be the atoms themselves. Under the heading "Atomi quibus experimentis asseri possunt" Bérigard described his experiment:

> In vase vitreo purissimus aer inclusus, nec a vento aut alio quod sciatur impulsus, tamen ad Solem ita expositus ut radij non totum collustrent, sed per foramen clausae fenestrae, ut saepe fit, medium pertranseant, oberrare videntur et ultro citroque concursare multa corpuscula, non tantùm in aere externo, ubi pulverem volaticum suspicaberis, sed etiam in eo qui multis annis vitro concluditur, et cuius pulvis, si quis est, iampridem fundum petere debuit. Atqui omnino nisi volitarent tenuia multa corpuscula, radio per duo foramina conclavis obscuri transeunte, nullus fieret luminis repercussus et si quis ibi conclusus oculos quàm maximè intenderet in eum radium, nihil tamen intueretur: At verò propius obtutum defigenti semper aliquid conspicitur, quod aliud esse non potest, quàm atomi, ad quas lumen impingens minima ex parte ad nos deflectitur, ferè enim totum inter atomorum vacuitates recta procedit.[27]

Among those who made the first, if cautious, steps toward a quantitative determination of atomic dimensions by means of experiments was Daniel Sennert. In a series of experiments designed to prove the existence and demonstrate the size of the atoms by chemical *resolutio* Sennert described, first of all, a distillation in which he made a stream of alcohol vapor pass through a sheet of writing paper that had been folded four times. From the density of the paper and its invisibly small pores one might imagine how small the atoms really were if they passed through it so freely. This was certainly an impressive observation, but again it was also a tacit reference to Lucretius, who said the same about filtration of

[25] Lucretius, *De rerum natura* 4.114–131; and Democritus, in Aristotle, *De anima* 1.2 (404a3); cf. Basso, *Philosophia naturalis* (cit. n. 19), p. 13; Gassendi, *Animadversiones* (cit. n. 24), Vol. I, p. 222; and Gassendi, *Syntagma philosophicum* (cit. n. 24) 1.3.7, p. 277.

[26] As historians of science (qua science) we tend to minimize the impact of merely fictional works upon scientific matters. Even superficial evaluation of the sources quoted by early modern adherents to the corpuscular theory shows, however, that their effect can be considerable. For the general impact of Lucretius's text see George Depue Hadzsits, *Lucretius and His Influence* (Our Debt to Greece and Rome, 12) (New York: Longman, 1935); and esp. Alfred Stückelberger, "Lucretius reviviscens: Von der antiken zur neuzeitlichen Atomphysik," *Arch. Kulturgesch.*, 1972, *54*:1–25.

[27] Berigardus, *Circulus Pisanus* (cit. n. 13), pp. 421–422.

solutions through paper.[28] Sennert went on to give examples of various distillations, comparing the enormous volume of vapor with myriads of atoms in it to the small droplets into which they condense:

> Dum etiam spiritus vitrioli, vel alij destillantur, corpusculis eiusmodi parvis, nondum tamen planè minimis, vas recipiens saepe per biduum vel triduum continuò plenum est, et singulis momentis aliquot myriades eiusmodi corpusculorum praesentes sunt, et sibi succedunt. Exigua tamen liquoris quantitas ex iis coëuntibus et condensatis provenit: ita ut, quae eodem momento praesentia sunt atoma corpuscula, quorum tamen aliquot myriades sunt, vix unam guttam constituant.[29]

In a similar vein is Sennert's comparison between the smoky wick of an extinguished candle, which was not even the size of a pea, and the huge volume of air that was filled with its smoke: "Et quanta inter corpus compactum et in atomos resolutum sit differentia, vel candela extincta docet. Si quis enim flammam è candela accensa flatu dissipet, ellychnium fumigans, quod vix pisi magnitudinem aequat, tantam continuò atomorum copiam emittit, ut magnum aëris spatium eâ repleatur."[30]

The language in which these observations were described abounded with quantitative statements about the duration of the experiment (*biduum vel triduum*), the number of corpuscles (*aliquot myriades*), the amount of the product (*vix unam guttam*), or the size of the candlewick (*vix pisi magnitudinem*). There is not, however, the vaguest idea of a quantitative methodology behind these indications. The language of the laboratory displays its figurative and rhetorical power, aimed at the imagination of the reader and his eventual persuasion. In tribute to the new scientific age, arguments needed support from the rhetoric of the experiment. But to do justice to Sennert, we have to admit that, in this case, even the most scrupulous quantitative experimenter would not have arrived at any result.

A few decades later Johannes Chrysostomus Magnenus, professor of medicine at Pavia, suggested exact figures for the size of an atom on the basis of impressive quantitative calculations. Taking Archimedes' *Sand-Reckoner* as a model, Magnenus estimated the number of particles in a grain of incense from the volume of air filled with its scent:

> Adverti non semel granum thuris combustum fumo ita dispergi, ut locum repleverit septingentis, et amplius millionibus se majorem. Ille enim locus grana hujuscemodi facile cepisset

secundum altitudinem	720
secundum latitudinem	900
in longitudine	1.200
in superficie	648.000
in area	777.600.000.

> Cum ergo nulla aeris sensibilis portio esset, quae odoros non haberet halitus granumque thuris aequaret cicerem, qui sine igne in partes sensibiles saltem mille dividi posset, sequitur particulas odoras sensibiles fuisse istius num[eri] 777.600.000.000. Atqui singulae illae particulae mixtae erant, nullamque fuisse probabile est, cui unus

[28] Lucretius, *De rerum natura* 2.391–397; and Sennertus, *Hypomnema* 3.1.1 (cit. n. 23), p. 118. The marginal heading is "Chymicae operationes atomos probant."
[29] Sennertus, *Hypomnema* 3.1.1 (cit. n. 23), p. 118.
[30] *Ibid.* The comparison also occurs in Gassendi, *Animadversiones* (cit. n. 24), Vol. I, p. 222.

Figure 1. *Daniel Sennert (1572–1637). Courtesy of the E. F. Smith Memorial Collection, University of Pennsylvania Libraries, and the Beckman Center for the History of Chemistry.*

> ad minimum elementalium atomorum millio inesset, unde, secundum hanc regulam, fuissent in hoc thuris grano, pisi magnitudinem non superante, atomi elementales ad minimum 777.600.000.000.000.000. Ex quibus patet, quantae sit parvitatis atomus una, conjicique potest, quantus sit atomorum numerus in toto universo.[31]

But what does it prove that the number of atoms computed in this way comes surprisingly close to modern figures, as a recent historiographer did not fail to underline?[32] Were these meditations on incense atoms really scientific calculations, or merely the outcome of a boring sermon Magnenus had to listen to in his parish church? Yet he was not the only atomist to be fond of playing with

[31] Magnenus, *Democritus reviviscens* (cit. n. 24), pp. 206–207; see also Stückelberger, *Antike Atomphysik* (cit. n. 6), pp. 282–285.

[32] Stückelberger, "Lucretius reviviscens" (cit. n. 26), p. 19: "Zum erstenmal ist hier in der Geschichte der Atomphysik der Schritt vom qualitativen zum quantitativen Denken gemacht worden, mit einer übrigens durchaus brauchbaren Methode—später sind allgemeine Atomgewichte durch Gase errechnet worden—, die auch zu einer erstaunlich zutreffenden Größenordnung führt: er errechnet eine Anzahl von ca. $7{,}7 \cdot 10^{19}$ Atomen in einem Weihrauchkorn"; cf. Stückelberger, *Antike Atomphysik* (cit. n. 6), p. 60.

numbers. In 1654 Walter Charleton published exactly the same calculation—probably a mere translation from Magnenus, though the author did not disclose his source. At least Charleton should have heeded the warnings of his hero Gassendi: referring to Archimedes' attempts to compute the number of sand grains that would fit into a poppyseed, the French philosopher had already pinpointed the methodological problems involved in transferring this kind of geometric reasoning to physical matters. His conclusion was that one must not apply to physics that which the mathematicians have demonstrated abstractly.[33]

In contrast to Gassendi, the author of *Democritus reviviscens* displayed a philosophically inconsistent attitude. Although he tried to imitate the Euclidean method of presentation, his work abounded with purely dialectical reasoning and syllogistic conclusions. After the detailed calculations quoted above, he freely admitted that, apart from conjectures, one could never know anything about the absolute or even relative sizes of atoms.[34] But since Magnenus's calculations have recently been called the beginning of the quantitative methodology in atomic physics, it might be worthwhile examining more closely the attitude of this allegedly scientific mind toward experience and experiment.

There is no doubt that Magnenus favored the empirical and mechanical spirit of his age. Among the axioms of his natural philosophy is the often-repeated principle that, in physical matters, one has to philosophize on the basis of experience and judge by the senses: "In iis, quae sub sensum cadunt, posita experientia oportet philosophari, sensibilia enim per sensus judicanda sunt." He even went so far as to claim that the results of precise experimentation should be taken as self-evident presuppositions in scientific reasoning: "Experientias accurate factas tanquam principia per se nota admittere."[35] However, this empiricism was embedded in a great number of purely abstract and speculative arguments. The same inconsistency applies to the six "proofs" Magnenus gave for the existence of atoms. Five of them stem from, and were defended on, philosophical grounds alone; the sixth at least was the "experience of the chemists," for which the author referred, if somewhat vaguely, to Sennert's *Hypomnema* 3.2.[36]

The only real experiment Magnenus presented on some five pages was taken from Jacques Gaffarel's *Curiositez inouyes sur la sculpture talismanique des Persans, horoscope des patriarches et lecture des estoilles* of 1629, a widely read and controversial compendium of natural magic. From this dubious source Mag-

[33] Walter Charleton, *Physiologia Epicuro-Gassendo-Charltoniana: Or a Fabrick of Science Natural upon the Hypothesis of Atoms* (London, 1654), 2.4, p. 114; Archimedes, *Arenarius* 2.4; and Gassendi, *Syntagma philosophicum* (cit. n. 24), 1.3.5, p. 265. For Gassendi's atomism see Bernard Rochot, *Les travaux de Gassendi sur Epicure et sur l'atomisme, 1619–1658* (Paris: Vrin, 1944); and Lillian U. Pancheri, "The Atomism of Pierre Gassendi: Ontology for the New Physics" (Ph.D. diss., Tulane Univ., 1972).

[34] Magnenus, *Democritus reviviscens* (cit. n. 24), p. 208: "At in his nihil aliud quam conjicere possumus, quis enim novit an atomi igneae majores, minoresve sunt aqueis, et terreis? quis dignoscit aerarum parvitatem, caelorum profunditates omnes, et extimam illam Beatorum sedem?"

[35] *Ibid.*, pp. 36 (the 11th of Magnenus's principles of corpuscular philosophy), 163.

[36] *Ibid.*, pp. 176–182. It is not clear whether Magnenus had ever read Sennert's *Hypomnema* 3.2, for in it Sennert developed his doctrine of mixture from the elements solely by the concurrence of their opposing qualities under the lead of a more noble form, supported by experimental evidence that the elements, if divided into minute particles, no longer oppose each other even if their qualities are contrary. Magnenus's first five principles are as follows. 1. Natura omnem refugit infinitatem. 2. Elementa ex minimis, ergo ex indivisibilibus; at elementa sunt materia prima; ergo materia prima ex indivisibilibus, ergo ex atomis. 3. Tot creationes in materia prima quot individua. 4. Unio non sine partibus; ergo partes non sine unione. 5. Impossibilitas partium infinitarum in continuo.

nenus took the then widely discussed story of a Polish physician who kept a collection of sealed glass vessels that contained finely ground flowers of various kinds. But when a candle was put underneath such a vessel containing the ashes of a rose, the corpuscles coalesced under the influence of the heat to form a perfect rose. When the candle was removed, the appearance disintegrated again into its atoms.[37] This strange experiment, which goes back to a report given by Joseph du Chesne in 1604, was originally presented as an example of palingenesis or resuscitation of living bodies from their ashes by virtue of the formative or seminal power inherent in their salts. Curiously enough, this Paracelsian paradigm acquired some fame among the proofs of the reality of the atoms later on. Etienne de Clave, the skilled chemist and physician who had intended to prove the truth of the scandalous anti-Aristotelian theses presented in 1624, was reported to have performed daily this experiment of reproducing an herb or a flower from its ashes.[38] The phenomenon was discussed even among the most respectable scientists of the time, but this is not the place to follow up the strange vicissitudes of the palingenesis experiment, the tradition of which can be traced down to Romantic *Naturphilosophie* and nineteenth-century debates over chemical vitalism.[39]

Microscopical Perception

It was more than merely a physical analogy to mathematical extrapolations when Daniel Sennert, after an exposition of the structure of clouds and smoke, concluded that from their small drops and particles one could infer the existence of ultimate particles. Atmospheric phenomena seemed especially well suited to support this approach, for according to the theory Aristotle put forward in his *Meteorologica,* they were not perfect mixtures but somewhat incomplete aggregates of the elements. Consequently Sennert stated that whoever is close to a cloud, for example, when hiking in the mountains, will be able to confirm that clouds are not continuous bodies but accumulations of atoms. Though this sounds like an empirical statement, it was almost certainly an allusion to Lucretius's theory of the formation of clouds.

[37] Magnenus, *Democritus reviviscens,* pp. 183–184. I have used the Latin translation of Jacobus Gaffarellus, *Curiositez inouyez, hoc est: Curiositates inauditae de figuris Persarum talismanicis, horoscopo Patriarcharum et characteribus coelestibus* (Hamburg/Amsterdam, 1678), pp. 97–99; see also Thorndike, *History of Magic* (cit. n. 3), Vol. VII, pp. 304–309. Martin Fichman's entry on Magnenus in the *Dictionary of Scientific Biography,* ed. Charles Coulston Gillispie, 16 vols. (New York: Scribners, 1970–1980), Vol. IX, pp. 14–15, is entirely misleading when it states that "much of the experimental evidence was drawn from Daniel Sennert's *Hypomnemata Physica* and Jacques Gaffarel's *Curiositez inouyez,*" without revealing the true nature of this "experimental" evidence.

[38] See (on Etienne de Clave) *Correspondance du P. Marin Mersenne,* ed. Marie Tannery and Cornelis de Waard, Vol. I (Paris: Presses Universitaires, 1945), p. 326; see also Iosephus Quercetanus, *Ad veritatem Hermeticae medicinae ex Hippocratis veterumque decretis ac therapeusi . . . responsio* (Paris, 1604), pp. 292–294. Du Chesne admitted to having performed the experiment unsuccessfully several times until, eventually, on a cold winter day he succeeded when a solution of salts extracted from stinging nettles froze into a block of ice displaying thousands of nettlelike structures (p. 296).

[39] See the contemporary survey by Gregorius Michaelis, *Notae in Jacobi Gaffarelli Curiositates* (Hamburg, 1676), pp. 249–253. Recent studies include Jacques Marx, "Alchimie et Palingénésie," *Isis,* 1971, *62*:274–289; Allen G. Debus, "A Further Note on Palingenesis," *Isis,* 1973, *64*:226–230; Joachim Telle, "Chymische Pflanzen in der deutschen Literatur," *Medizinhistorisches Journal,* 1973, *8*:1–37; and François Secret, "Palingenesis, Alchemy and Metempsychosis in Renaissance Medicine," *Ambix,* 1979, *26*:81–92.

> Meteora certè pleraque tantùm sunt Elementarium atomorum varia congeries. Exhalationes enim et vapores, quod vulgò creditur, non corpora continua sunt, sed congeries infinitarum atomorum: id quod ex vaporibus ex aqua, quae ad ignem calefit, ascendentibus manifestum est. Hi enim etsi procul corpus continuum videantur; tamen qui prope est, aut qui in montibus aere nebuloso ambulat, vel visu discernere potest, vapores tales non esse continua corpora sed atomorum congeriem. Nubes nihil aliud sunt, nisi infinita atomorum multitudo.[40]

Seventeenth-century science was fond of the small: it discovered worlds in a drop of water, and it developed the apparatuses to open up perspectives hitherto unseen. There was a widespread enthusiasm for the magnifying glass and for the microscope, which had just been invented. Microscopy became a preoccupation with the Baconians.[41] The new instruments made it possible to come closer to the details, closer to reality, and—so it was assumed—closer to truth. What had been the exclusive domain of speculation or extrapolation for centuries was now at least potentially observable.[42] The possibilities of optical ingenuity seemed almost unlimited. In a chapter on the size of the atoms Gassendi meditated about the degree of refinement to which the borderline between man's and nature's subtlety might be extended by means of the microscope (*engyscopium*):

> Sanè enim quae nostro visui apparent esse minima, ipsi naturae maxima sunt; ac dici potest, ubi nostra industria, subtilitásque desinit, inde incipere industriam, subtilitatémque naturae. Quippe, ut videas artifices qui annuli pallâ concludant tot illas horologij parteis, quas nisi turris capacitate rudiores fabri non valeant; ita Natura plureis parteis in milij grano distinguere, quàm homo possit in Caucaso, imò in toto globo telluris. Videri id incredibilius poterat maioribus nostris, ante inventionem Engyscopij; nunc verò, quî possit, cùm videamus granum detritissimi pulveris piso amplius repraesentari, et cum distinctissimis quidem facieculis, angulísque, de quibus ne venire quidem in mentem suspicio potuisset: adeò ut cùm diameter corpusculi Engyscopio visi sit propemodum centupla ad diametrum citra ipsum visam, dicere liceat ipsum saltem ex decies centenis millibus partium esse conflatum. Saltem, inquam, nam cogita et Engyscopium perfectius, quàm hactenus viderimus, et acutissimum quemque visum consistere semper infra naturae industriam; et agnosces denique rem abire propè in immensum.[43]

What had been a merely potential aptitude of the instrument to Gassendi, carefully restricted by the *saltem* of his epistemological reservation, was presented as an empirical fact by the English physician Henry Power only a few years later. In his *In Commendation of y^{e} Microscope,* written about 1661, the new optical means became a new, artificial eye to help the blindness of the aged world,

[40] Sennertus, *Hypomnema* (cit. n. 23), 3.1.1, p. 118; cf. Lucretius, *De rerum natura* 6.451–523, esp. 468–469: "Patere res ipsa et sensus, montis cum ascendimus altos."

[41] Charles Webster, *The Great Instauration: Science, Medicine, and Reform, 1626–1660* (London: Duckworth, 1975), pp. 165, 170.

[42] See Francis Bacon's often-quoted statement, "quale perspicillum si vidisset Democritus, exiluisset forte, et modum videndi atomum (quem ille invisibilem omnino affirmavit) inventum fuisse putasset"; Francis Bacon, *Novum Organum* 2.39 (1620), in *The Works of Francis Bacon,* ed. James Spedding, Robert Leslie Ellis, and Douglas Denon Heath, 14 vols., Vol. I (London, 1857), p. 307. For the ambiguous relationship between the new optical instruments and the question of truth see Hans Blumenberg, "Das Fernrohr und die Ohnmacht der Wahrheit," in Galileo Galilei, *Sidereus Nuncius: Nachricht von neuen Sternen,* ed. Hans Blumenberg (Frankfurt: Insel, 1965), pp. 7–75.

[43] Gassendi, *Animadversiones* (cit. n. 24), Vol. I, p. 207; verbatim also in Gassendi, *Syntagma philosophicum* (cit. n. 24), 1.3.6, pp. 268–269.

By whose augmenting power wee now see more
then all the world Has euer donn Before.
Thy Atomes (Braue Democritus) are now
made to appeare in bulk & figure too.
When Archimide by his Arithmatick,
numbred the sands, had hee But knowne this trick.
Hee might haue seene each corn a massy stone,
& counted them distinctly one by one.[44]

In his *Experimental Philosophy,* the first English book on microscopy, antedating by less than a year Robert Hooke's famous *Micrographia: or, Some Physiological Descriptions of Minute Bodies made by Magnifying Glasses* (London, 1665), Power, writing in 1661, claimed enthusiastically that "our Modern Enginge (the Microscope)" enabled men to

> see what the illustrious wits of the Atomical and Corpuscularian Philosophers durst but imagine, even the very Atoms and their reputed Indivisibles and least realities of Matter. . . . indeed, if the Dioptricks further prevail . . . we might hope, ere long, to see the Magnetical Effluviums of the Loadstone, the Solary Atoms of light . . . , the springy particles of Air, the constant and tumultuary motion of the Atoms of all fluid Bodies, and those infinite, insensible Corpuscles which dayly produce those prodigious (though common) effects amongst us: And though these hopes be vastly hyperbolical, yet who can tel how far Mechanical Industry may prevail; for the process of Art is indefinite, and who can set a *non-ultra* to her endeavours?[45]

To Henry Power this was certainly more than the selling rhetoric and pretentious phraseology so common in prefaces. Among the many microscopical observations described in his *Experimental Philosophy,* mainly of insects and plants, there were also a few of chemicals. For instance, Power studied traces of running mercury and found that the "atoms of Quick-silver . . . seemed like a globular Looking-glass." From the heterogeneity and particulate structure of a "cosmetical mercury precipitate" he was viewing through his lenses, he inferred that the metal atoms remain unaltered when a compound is formed and retain invisibly their true nature: "You may most plainly and distinctly see all the globular Atoms of current and quick [mercury]; besprinkled all amongst those Powders, like so many little Stars in the Firmament: which shews that those Chymical Preparations, are not near so purely exalted and prepared, as they are presumed to be; nor the Mercury any way transmuted, but meerly by an Atomical Division rendred insensible."[46] Yet as a serious scientist Power had to admit that he had not succeeded in seeing any corporeal effluvia by means of his optical device, not even those of camphor or the transpiration of human skin, although a Dr. Highmore, perhaps with better eyes and a more powerful microscope, had claimed to have seen the magnetic effluvium "in the form of a Mist to flow from

[44] Quoted from Thomas Cowles, "Dr. Henry Power's Poem on the Microscope," *Isis,* 1934, *21*:71–80, on p. 71, lines 9–16.

[45] Henry Power, *Experimental Philosophy, In Three Books: Containing New Experiments, Microscopical, Mercurial, Magnetical. With Some Deductions, and Probable Hypotheses, raised from them, in Avouchement and Illustration of the now famous Atomical Hypothesis* (London, 1664), Part I, sigs. b2r, c2v–[c3r]. See Charles Webster, "Henry Power's Experimental Philosophy," *Ambix,* 1967, *14*:150–178.

[46] Power, *Experimental Philosophy,* Observation 34, p. 43; Observation 35, p. 44.

the Load-Stone." Power, the meticulous observer, was entirely conscious that such an observation, could it be proved to be true, would be the *experimentum crucis* for matter theory: "This Experiment indeed would be an incomparable Eviction of the Corporeity of Magnetical Effluviums, and sensibly decide the Controversie 'twixt the Peripatetick and Atomical Philosophers."[47]

However stimulating these instruments were for the study of biology, their meaning for matter theory was ambiguous. Jungius used the magnifying glass to study textile fabric and apparently homogeneous substances such as polished surfaces. He observed that they were in fact always heterogeneous if viewed through a microscope (*anchiscopium*). In 1633, commenting on Sennert's *Epitome scientiae naturalis* of 1618, in which Sennert had shown that arguments from geometry about divisibility and continuity must not be applied to the physical sciences, Jungius remarked that until then no physical body had ever been proved to be entirely homogeneous. For no surface could be so smooth that one could not think of a more powerful microscope that would reveal its true discontinuity. Consequently, Jungius categorically stated that continuity was foreign to the realm of sensuous experience. On the other hand he had to admit that if there were no truly continuous parts in the end, infinite progression and divisibility would result. This was the vicious circle of every observational approach to the atoms.[48] Methodological difficulties and a contradictory epistemology arose if one attempted to model the real after the visible.

Material Transport

The next type of argument is on a similar level. Different kinds of transport phenomena were considered in which material substances appear or disappear unnoticed. The standard examples are well known: Smell is an efflux of corporeal particles. Clothes that are hung near the seashore become wet and dry again in the sunshine, but no vapors can be observed. A ring on the finger gets worn out, and so do tools and road surfaces, and even a stone is hollowed by constant drops of water. Diminution and growth and the almost imperceptible loss of moisture by bodies, such as the drying of bread or the slow evaporation of liquids, are material processes, although the flux of material cannot be observed.[49] In all these cases, quantitative change of material substances was recorded, and from this the existence of invisible parts of matter could be inferred. This was little more than an application of the theory of effluxion or *ἀποῤῥοαὶ* proposed by Empedocles, Democritus, and Asclepiades of Prusa and eventually expounded in Lucretius's poem.[50] In the seventeenth century these examples were repeated again and again, and similar ones were added. It was entirely in accord with the

[47] *Ibid.*, Observation 51, "Of Aromatical, Electrical, and Magnetical Effluxions," p. 51. The English physician and atomist Nathaniel Highmore was a friend of William Harvey's. The observation referred to seems not to come from his published writings.

[48] Joachim Jungius, *Exercitatio VI de continuo,* 1633, Staats- und Universitätsbibliothek Hamburg, Jungius-MSS, Wo. 24 (1), between fols. 24 and 25. The epistemological antinomy involved in the application of microscopy to the question of atomism is developed further in Christoph Meinel, " 'Das letzte Blatt im Buch der Natur': Die Wirklichkeit der Atome und die Antinomie der Anschauung in den Korpuskulartheorien der frühen Neuzeit," *Studia Leibnitiana,* 1988, *20* (in press).

[49] Lucretius, *De rerum natura* 1.298–299, 305–310, 311–321, 322–328. The water that abrades the stone in finite portions is already an Aristotelian example; see Aristotle, *Physics* 8.3 (253b15–23).

[50] Stückelberger, "Empirische Ansätze" (cit. n. 6), passim.

traditional line of argumentation when Daniel Sennert, in 1619, discussed the growth of chalk and stalactites from clear mineral waters, phenomena which, in his opinion, pointed to the corpuscular structure of matter. Again the observer's surprise over nature's mysteries is used as the point of departure for a rhetorical stratagem: "Cùm tamen aqua quae decurrit limpidissima sit, ut quis mirari possit, quomodo ex tam perspicua et clara aqua corpus tam crassum fieri queat. Proculdubio in talibus aquis mineralis et lapidea materia in minimas particulas resoluta fuit, quae postea suo concurso et *συνκρίσει* saxeum et durum corpus constituunt."[51]

It is difficult to believe that this kind of argumentation was taken as a scientific, empirical demonstration. For what did it prove except that there is material transport that cannot be seen? Perhaps three aspects should be given particular consideration: the phenomena dealt with suggested that the ultimate constituents of matter were potentially observable by extended experimental effort, deductible by analogy, and provable by virtue of their actions. There is little doubt, however, that these phenomena were not adequate for definitively deciding the question of matter, and they were certainly not understood in this manner by contemporaries. Yet the frequent occurrence and repetition of these observations, the persuasive idea that truth should be visible or could be thought of in a pictorial way, infiltrated scholarly discourse and the very language of science. Atomism was an enticingly pictorial image of reality. The wealth of appealing and immediately convincing images offered by Lucretius's poem supplied the scheme according to which material change was assumed to occur in nature. Consider Bérigard's experiment: the Lucretian motes in a sunbeam, which might have been simple dust particles, could of course not be taken seriously by the more sophisticated contemporaries of Galileo. Had not the microscope shown that even the smallest items were in reality composed of much smaller ones? Hence Bérigard made that very careful and reasonable experiment with sealed glass flasks to exclude all possible dust and turbulence in the air, and he actually saw the atoms. To be precise, he saw something "quod aliud esse non potest, quàm atomi," just as Sennert perceived them in the droplets of fog and clouds or Henry Power in the mercury preparations under his microscope.[52] Why then should they proceed any further, why devise more sophisticated experiments, why bother about the quantitative side, and why seek proofs, when the atoms were more than evident? The question of atomism had become rather a matter of plain evidence than of proof or confirmation.

Condensation and Rarefaction

Unlike the instances of analogical extrapolation from sense perception, the problems that arose from condensation and rarefaction and, above all, from the question of the vacuum belong to the field of physical experimentation proper, in which one would expect more convincing departures from the traditional ways of reasoning. In ancient atomism, with its hard and impenetrable atoms, change required motion, and motion required a void space to move into. The void was

[51] Sennertus, *De consensu et dissensu* (cit. n. 23), p. 231. See also Sennertus, *Hypomnema* 3.1.1 (cit. n. 23), p. 117.

[52] Berigardus, *Circulus Pisanus* (cit. n. 13), p. 422.

where the atoms were not; it formed the gaps between the particles. The nature of this void, however, was a matter of endless controversy until the eighteenth century. Yet as far as the experimental side was concerned, the question had not been advanced beyond the ancient state of affairs.[53] Basically two alternatives were discussed: first, the continuous or three-dimensionally extended void (*vacuum separatum*), and, second, the more widely received idea of a discontinuous, interspersed void between the particles of matter (*vacuum disseminatum*). The latter was less difficult to accept since it did not imply the existence of a space whose dimensions were not defined by the surface of bodies.

There was one classic experiment that could be interpreted as evidence for the discontinuous structure of matter and the existence of microvacua: a vessel filled with loose ashes was reported to hold as much water as an empty vessel because the tiny ash particles are received within the pores or vacua of the water. Aristotle ascribed this observation to those who believed in the void, but he duly rejected it on the ground that two bodies cannot occupy the same space simultaneously. The observation was indeed puzzling and kept the medieval commentators busy.[54] Most of them favored the explanation given by Averroes, who, while admitting that he had never viewed the phenomenon, denied the existence of vacua. Instead, he assumed a partial corruption of water by the ashes to be responsible for the shrinkage in volume.

Francis Bacon was presumably the first to disprove the phenomenon in question experimentally. In his posthumously published *Sylva sylvarum* he used his results to ridicule the old quarrel:

> It is strange how the ancients took up experiments upon credit, and yet did build great matters upon them. The observation of some of the best of them, delivered confidently, is, that a vessel filled with ashes will receive the like quantity of water that it would have done if it had been empty. But this is utterly untrue; for the water will not go in by a fifth part. And I suppose that that fifth part is the difference of the lying close or open of the ashes; as we see that ashes alone, if they be hard pressed, will lie in less room; and so the ashes with air between lie looser, and with water closer. For I have not yet found certainly, that the water itself, by mixture of ashes or dust, will shrink or draw into less room.[55]

This was a clear departure from the traditional way of reasoning. In reality, however, the matter was not as simple as one might believe from Bacon's straightforward refutation. In the second part of Gassendi's *Syntagma philosophicum,* published posthumously in 1658, the ash experiment was referred to as the traditional proof for the existence of an interspersed void (*inane interspersum*) but rejected on both experimental and philosophical grounds ("experimentum explorando falsum deprehenditur, uti et principiis naturae repugnat"). Instead, the French philosopher proposed another and more convincing experiment in support of corpuscles and *spatiola inania* in a solution. He saturated water

[53] The best account is Edward Grant, *Much Ado about Nothing: Theories of Space and Vacuum from the Middle Ages to the Scientific Revolution* (Cambridge/London/New York: Cambridge Univ. Press, 1981). For the experimental side see Pierre Duhem, *Le système du monde,* Vol. III (Paris: Hermann, 1958), pp. 121–168; and Charles B. Schmitt, "Experimental Evidence for and against a Void: The Sixteenth-Century Arguments," *Isis,* 1967, *58*:352–356.

[54] Aristotle, *Physics* 4.6 (213b21–22, 214b7–8); see Grant, *Much Ado about Nothing* (cit. n. 53), pp. 71–72.

with ordinary salt and found, to his great surprise, that this solution was still as capable of dissolving alum as pure water would have been: "Experiundi gratiâ Alumen conieci in Aquam per complures dies sale impraegnatum; ac tum, non sine quodam stupore succedere coniecturam vidi: scilicet alumen perinde, ac si aqua sale caruisset, exsolutum fuit; neque id modò, sed et consequenter alios praeterea saleis exsolvit, et, ut paucis dicam, ostendit quàm varia, insensibilia licet, loculamenta contineret."[56]

From this Gassendi concluded that there must be various differently shaped microvacua or *loculamenta* in the water, each kind of which receives exactly one kind of corpuscle, for example, a cubic space a cubic corpuscle such as salt, and an octahedral space an octahedral one such as alum.[57] Although Gassendi's account was somewhat vague regarding the decrease or increase of volume during this process, he must have assumed that the volume of the solution remains unaltered. Otherwise the entire argument would have been pointless. But was it not absurd to assume that the quantity of matter remains constant when another quantity is added? This is exactly what Jean-Baptiste Morin, a somewhat obscure and dubious French antiatomist and anti-Copernican, thought when he read Gassendi's report. He repeated the experiment more carefully in a glass flask with a graduated neck and found that when salt, alum, and sugar were added to water, the volume of the resulting solution was greater than that of pure water.[58] From textual evidence alone, it is difficult to judge who was correct, Gassendi or Morin. At least, the controversy could not be as easily settled by a single experiment as Bacon had assumed. In fact, either observation, the constant or the increased volume, may have been correct: for there are indeed certain salts that do not increase the volume of water when they are dissolved, and water-free alum is one of them.

Apart from explaining dissolution, the assumption of discontinuous matter and interparticulate vacua seemed especially helpful in explaining the coherence of bodies. The standard experiment was the drawing apart of two perfectly flat surfaces from direct contact, first described by Lucretius to show that during this action a void must result, since the air cannot fill the entire opened space instantaneously.[59] Originally supposed to prove the existence of a vacuum, the experiment soon acquired a crucial position among the proofs for its nonexistence. It was in this latter sense that Galileo referred to it, for in his opinion the coherence of surfaces was a perfect illustration of nature's abhorrence of a vacuum. He availed himself of the occasion to describe, through the mouth of his spokesman Salviati, a hydrostatic experiment, based upon Hero's *Pneumatica* and designed to measure the breaking force of a water column, which would give him a quantitative value for what he called "la resistenza del vacuo." It was exactly this

[55] Francis Bacon, *Sylva sylvarum; or, A Natural History* 1.34 (1627), in *Works of Bacon* (cit. n. 43), Vol. II (London, 1859), p. 354.

[56] Gassendi, *Syntagma philosophicum* (cit. n. 24), 1.2.3, p. 195; see also p. 196.

[57] The same experiment and the same conclusions reappear several times in the seventeenth century. Charleton, *Physiologia Epicuro-Gassendo-Charltoniana* (cit. n. 33), p. 31, probably took it verbatim from Gassendi. A more critical statement was that of Bérigard, who objected that there was no reason why a cubic particle, e.g., should not be received within a bigger octahedral space; see Berigardus, *Circulus Pisanus* (cit. n. 13), p. 422.

[58] Johannes Baptista Morinus, *De atomis et vacuo contra Petri Gassendi Philosophiam Epicuream* (Paris, 1650), pp. 19–20.

[59] Lucretius, *De rerum natura* 1.385–397.

"resistance of the vacuum" that he believed to be responsible for the strength and rupture tension of solid bodies. The melting of a metal, for instance, could then be explained by an influx of fire particles into the originally void spaces, so that the *vacuola* disappear and the hard metal loses cohesion. But as Galileo did not believe in an extended vacuum, he had to assume that the size of these *vacuola* is almost zero, whereas their number is beyond limit. Consequently, he assumed that solid bodies consist of an infinite number of atoms that have no extension at all (*atomi non quanti*), and an equally infinite number of dimensionless spaces between them.[60] Strangely enough this implied that liquids were entirely continuous, because they lacked internal cohesion—a conclusion that some of Galileo's contemporaries arrived at for similar reasons. Still, the physical explanation of coherence remained a major difficulty within the corpuscular framework. Why do metals melt if heated, but not if finely crushed with a hammer? Why is silver liquefied by acid, but not if ground with a file?[61]

The problem of coherence and the interspersed void became even more acute in condensation and rarefaction.[62] According to the Aristotelian doctrine a given amount of matter could assume, at different times, contrary qualities; and since dense and rare are contrary, the same amount of matter could occupy different volumes at different times. The standard example was the change from water to air or the change in volume that occurred if a liquid was heated or cooled.[63] Aristotelian matter was capable of stretching and contracting over a wide range of volumes without losing its continuity. There was indeed no corpuscular explanation of a similar simplicity available during the seventeenth century. Few authors would have admitted that the interspersed vacua could be blown up to a size that would account for the observed change of volume during evaporation. Otherwise, they would have had to admit a continuous vacuum. Even after the Torricellian vacuum had been experimentally demonstrated in 1643, it was by no means unanimously considered to be entirely void. Thus its impact on the corpuscular theory was doubtful. The first atomist to discuss the Torricellian experiment in great depth was presumably Gassendi in his *Animadversiones in decimum librum Diogenis Laertii,* completed in 1646, but even his account of the extended void remained vague about its meaning for the theory of matter.[64] Besides, Gassendi believed it was solely an artificial phenomenon with no equivalent in nature.

Instead of admitting the void, most authors held that there was some kind of ether or spirit between the impenetrable particles of gross matter. This medium filled the spaces between the vapor atoms and glued the corpuscles of solid bodies together. This was also the explanation favored by Gorlaeus, who identi-

[60] Galileo Galilei, *Discorsi e dimostrazioni matematiche* (1638), in *Le Opere di Galileo Galilei,* edizione nazionale, 20 vols. (Florence: Barbèra, 1964–1966), Vol. VIII (1965), pp. 59, 62–63, 66–67. To illustrate this last assumption about atoms and spaces Galileo used the paradox known as Aristotle's wheel; see Israel E. Drabkin, "Aristotle's Wheel," *Osiris,* 1950, *9*:162–198. See also the works on Galileo's theory of matter cited in n. 21 above.

[61] Galileo, *Discorsi* (cit. n. 60), Vol. VIII, p. 85. See also E. C. Millington, "Theories of Cohesion in the Seventeenth Century," *Ann. Sci.,* 1941/47 (publ. 1945), *5*:253–269.

[62] Grant, *Much Ado about Nothing* (cit. n. 53), pp. 70–74.

[63] Aristotle, *Physics* 4.9 (217a20–b19); and Aristotle, *De generatione et corruptione* 1.5 (321a10–29).

[64] Gassendi, *Animadversiones* (cit. n. 24), Vol. I, pp. 424–444; and Gassendi, *Syntagma philosophicum* (cit. n. 24), 1.2.5, pp. 203–216.

fied it with the air, which he believed to be capable of neither expansion nor compression. Basso imagined a *spiritus* or a very thin corporeal substance to go between the particles of expanding air in order to prevent the formation of a vacuum.[65] It should not be overlooked, however, that the reintroduction of an active spirit or ether into atomism undermined the advantages and theoretical consistency of the corpuscular theory.[66] If a mechanical explanation of condensation and rarefaction was sought, the ether was certainly not a convincing solution. Other alternatives were equally weak. Magnenus, who strongly rejected the vacuum and denied any real condensation or rarefaction, offered a strange blend of atomism and Aristotelian stretchability of matter. He endowed his atoms with the ability to expand almost indefinitely in two dimensions while the third dimension shrinks accordingly, so that the surface remains constant, or "isoperimetric" as he termed it. The idea was that an extremely expanded atom would dilute and augment, so to speak, the space it occupied before. In this way expansion could be explained without admitting the inflation of interparticulate vacua. From these examples it is clear that, in contrast to classical atomism, the vacuum, be it dispersed or extended, was not a *conditio sine qua non* for a corpuscular theory in the seventeenth century. Plenist corpuscularians such as Bérigard, Basso, or Descartes witness that it was entirely acceptable to assume corpuscles without admitting the void.[67]

Atoms of Light

One last type of physical argument should be mentioned at least briefly: the evidence of a particulate structure of matter derived from nonmaterial phenomena such as sound, heat, magnetism, electricity, or light. Most of the early attempts to substantialize or materialize the immaterial would lead us too far away from the main purpose of this study. They originate from ancient atomism and were taken up again by many seventeenth-century authors. Explicit formulations, however, such as Basso's atoms of heat and cold, Gorlaeus's atoms of time, or the quality-atoms imagined by Bérigard, remained exceptional.[68] Only light was frequently regarded as a substance that consisted of tiny particles, thin

[65] Cornelis de Waard, *L'expérience barométrique, ses antécédents et ses explications: Etude historique* (Thouars: Imprimerie Nouvelle, 1936), pp. 29–32, 85–90; Gorlaeus, *Exercitationes philosophicae* (cit. n. 10), pp. 248–249; and Basso, *Philosophia naturalis* (cit. n. 19), p. 300. As to the nature of this subtle matter, Basso pointed to some kind of Stoic spirit or ether (p. 306).

[66] Lasswitz's judgment is especially harsh in that regard: "Die intramolekularen Zwischenräume können daher wieder nur durch etwas ausgefüllt werden, das ebenfalls ein Körper ist und doch eigentlich kein Körper sein soll. Es ist ein durch Abstraktion von allen empirischen Qualitäten gewonnenes Destillat, ein verblaßter, unklarer Körper, heiße er nun Luft, Äther oder Spiritus, durch dessen Einschaltung alle jene Schwierigkeiten wieder eingeführt werden, die der Begriff des Korpuskels ablösen sollte. Gibt es überhaupt kontinuierliche, qualitative Substanzen, so hat die Unveränderlichkeit der Korpuskeln ihren systematischen Wert vollständig verloren." Lasswitz, *Geschichte der Atomistik* (cit. n. 1), Vol. I, p. 517.

[67] Magnenus, *Democritus reviviscens* (cit. n. 24), pp. 415–428, 254, 262. For Descartes's spongelike concept of rarefaction see Renatus Descartes, *Principia philosophiae* (1644), 2.6–7, in *Oeuvres de Descartes*, ed. Charles Adam and Paul Tannery, 13 vols. (Paris: Vrin), Vol. VIII (1982), Pt. 1, pp. 43–44. Descartes's theory of matter occupies a somewhat peculiar position. See also Boas, "Mechanical Philosophy" (cit. n. 1), pp. 442–460; and Francesco Trevisani, "La teoria corpuscolare in Cartesio dal 'Traité du Monde' ai 'Principia,' " in *Ricerche sull'atomismo* (cit. n. 1), pp. 179–223.

[68] For Basso see Basso, *Philosophia naturalis* (cit. n. 19), pp. 413–421; and Zanier, "Macrocosmo corpuscolaristico" (cit. n. 19), pp. 99–109. On Gorlaeus see Lasswitz, *Geschichte der Atomistik* (cit. n. 1), Vol. I, pp. 458–459. For Bérigard see Berigardus, *Circulus Pisanus* (cit. n. 13), pp. 418–425.

enough to go through the pores of even hard and dense bodies. Lucretius had imagined atoms of light in order to explain the almost instantaneous transmission of light and images through space. Such atoms were extensively used by Bérigard and questioned by Gorlaeus, reflecting, however, more of a literary tradition than an empirical one. This is equally true for Gassendi, whose theory of light and vision was little more than a compromise between the ancient doctrine of corpuscular effluvia, the Lucretian *simulacra,* and Scholastic assumptions about the propagation of immaterial species through a medium.[69] In that regard the Cartesian theory of light is remarkable, since it made contact with experience and optical experimentation at various points, even if derived from an a priori conception of matter.[70] In purely optical treatises, on the other hand, little reference to matter theory is to be found. After all, optics was then a branch of mathematics or physiology, the methods and results of which were not normally considered to solve physical puzzles.

It is, therefore, on the borderline between physics and optics that we meet with an early example of how optical observations interacted with matter theory. In a series of letters exchanged between 1606 and 1608, Thomas Harriot and Johannes Kepler discussed the phenomenon of partial reflection and partial transmission of light in diaphanous bodies. The question was, how could an apparently continuous body transmit and reflect at the same time? Harriot imagined that the continuity was only in our senses, whereas in reality some corporeal parts at the surface resist the rays and therefore reflect, while other rays penetrate into the vacua between them, are reflected within the body, and leave it, scattering in many directions. The most striking example of this kind was probably gold, an entirely homogeneous, dense, and opaque body that reflects light like a mirror. But a thin gold foil reflects and is translucent at the same time. For Harriot, it seemed absurd to assume that a single homogeneous substance can be endowed simultaneously with two opposing qualities, transparency and opacity. Kepler, however, did not want to follow Harriot *ad atomos et vacua* and suggested keeping optics and matter theory distinct and accepting exactly this contradictory assumption.[71]

We cannot go into the many difficulties that arose from argumentation based upon the corpuscular nature of light. It seems to have played but a minor role in seventeenth-century atomism, except for the conventional explanation of transparency and diaphaneity by assuming that atoms of light pass through the pores of matter. But it must be remembered that, in the tradition of Newton's *Opticks,* the corpuscular nature of light became a most powerful argument in eighteenth-century theories of matter.[72]

[69] Lucretius, *De rerum natura* 4.176–215; Berigardus, *Circulus Pisanus,* pp. 426–430; Gorlaeus, *Exercitationes philosophicae* (cit. n. 10), p. 109; Gassendi, *Animadversiones* (cit. n. 24), Vol. I, pp. 236–260; and Gassendi, *Syntagma philosophicum* (cit. n. 24), 1.4.11–12, pp. 421–441. For the details of Gassendi's theory see Rochot, *Travaux de Gassendi* (cit. n. 33), pp. 100–102; and Wolfgang Detel, *Scientia rerum natura occultarum: Methodologische Studien zur Physik Pierre Gassendis* (Quellen und Studien zur Philosophie, 14) (Berlin/New York: de Gruyter, 1978), pp. 197–204.

[70] A. I. Sabra, *Theories of Light from Descartes to Newton* (London: Oldbourne, 1967), pp. 17–135.

[71] Harriot to Kepler, 2 Dec. 1606, in Johannes Kepler, *Gesammelte Werke,* ed. Max Caspar (Munich: Beck), Vol. XV (1951), pp. 365–368, on pp. 367–368; and Kepler to Harriot, 2 Aug. 1607, *ibid.,* Vol. XVI (1954), pp. 31–32, on p. 32. See also Robert Hugh Kargon, *Atomism in England from Hariot to Newton* (Oxford: Clarendon, 1966), pp. 26–27. For a critical reassessment of Harriot's atomism see Henry, "Thomas Harriot" (cit. n. 9).

[72] For the role of optical arguments in Newtonian matter theory see Arnold Thackray, " 'Matter in

Chemical Change

The "chemical" arguments proposed in support of the atomic view of matter fall basically into two categories: arguments that refer to processes during which a new *mixtum* or compound is generated, and proofs based upon the recovery of constituents from a mixture. In either case an explanation was required of how distinct particles interact and of how, from this interaction, new qualities emerge that were not originally present in the reactants. The emergence of a new form during substantial alterations, the so-called *eductio formae,* was indeed the great theme of early seventeenth-century Peripatetic theory of matter.[73] The traditional alternative explanations were descent of the form from the *forma caeli* or from a *dator formae,* and eduction from the potentiality of matter. Divorced from these learned speculations, the common attitude of metallurgists and practical alchemists was to ignore such abstract questions while naively taking the original reactants as the true constituents of a compound. Was it not reasonable to assume, for example, that the ingredients required to make up a complicated medicine were actually present in this preparation, with all their respective virtues? This pragmatic solution was favored by many iatrochemical authors. They were trained in the laboratory and little troubled by philosophical scruples. Jean Beguin's *Tyrocinium chymicum* of 1610 is a well-known example of this kind of approach.[74] It was not apt, however, to satisfy the needs of a natural philosopher. Consider a sweet and ripe fruit, said Giovanni Nardi, the editor of a Florentine edition of Lucretius's *De rerum natura,* attacking Sennert's corpuscular interpretation of substantial change: where were the ripeness and sweetness beforehand? The same little part (*eadem portiuncula*) that was previously astringent and bitter is now soft and sweet, but no significant change of weight has occurred. How then could this maturation be explained without admitting a new substantial form?[75]

Similar difficulties arose when decompositions such as chemical analyses were considered. The products that resulted from dissolution or *diacrisis* were commonly believed to be "parts" of the original compound. The terms *part* or *constituent,* sometimes *element,* implied the relation between a whole and its parts. Though this seems fairly reasonable, it led to incredible difficulties if applied to chemical processes. For whether something was regarded as composition or decomposition was often a matter of chance. As long as quantitative alterations, especially the decrease or increase of weight, were not systematically taken into account, there was no means of distinguishing between the two alternatives. Consequently, the dissolution of wood by fire would result in its "parts" of smoke and ash, the dissolution of milk in its "parts" of whey, butter, and cheese.

It is easy to understand that here purely mechanical action, and especially

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a Nut-Shell': Newton's Opticks and Eighteenth-Century Chemistry," *Ambix,* 1968, *15*:29–53; and Henry John Steffens, *The Development of Newtonian Optics in England* (New York: Science History Publications, 1977), pp. 27–54.

[73] Emerton, *Scientific Reinterpretation* (cit. n. 8); and Gregory, "Studi sull'atomismo, II" (cit. n. 10), pp. 55–62.

[74] R. Hooykaas, "The Discrimination between 'Natural' and 'Artificial' Substances and the Development of Corpuscular Theory," *Archives Internationales d'Histoire des Sciences,* 1948, *1*:640–651, on p. 643; and Hooykaas, "Experimental Origin" (cit. n. 1), p. 77.

[75] Titus Lucretius Carus, *De rerum natura libri VI unà cum paraphrastica explanatione et animadversionibus Joannis Nardii* (Florence, 1647), p. 37.

local motion, was not a sufficient explanation for the requirements of a chemical philosophy of matter, though some kind of motion was generally accepted as a prerequisite for the formation of a compound. But as Magnenus stated it, any undirected local motion of particles would account for disintegration only, not for concord and unition.[76] This then was the point of entry for additional hypotheses that did not originally belong to or were even contradictory to the principles of atomism. Assumptions of this kind were the corporeal ether, the active spirit, Neoplatonic concepts of sympathy and antipathy, or the teleology of noble or directing forms that act upon moving particles.

It is significant that Sennert explicitly admitted that, given the dimness of human cognition, there was no way of proving the mechanism by which the unity of parts was brought about and the form of the new compound generated. Practical chemist as he was, he preferred to leave these questions to others and went on to argue that at least one thing was certain, namely, that every mixture could be resolved into those parts out of which it was originally constituted. In other words, the substantial identity of the constituent parts must persist unchanged; otherwise there would be a generation of new constituents during the process of resolution and decay: "Hoc certum est, mistum quodlibet in ea, è quibus primò constitutum est, resolvi posse: et proinde formas elementorum non aboleri. Aliàs enim in resolutione et putredine fieret nova elementorum generatio."[77]

This was a most important step in the "chemical" argumentation in favor of corpuscles. For now it was no longer necessary to deal exclusively with the process of substantial change and the emergence of new qualities. Instead the question of the corpuscles' existence was reduced to a test of identity in a cyclic process that could easily be performed by the chemical means of the time. If then the identity of the original reactants and the products of decomposition could be demonstrated experimentally, the persistency of this material carrier would have been proved, no matter how many alterations had meanwhile occurred. This was clearly a departure from the former preoccupation with the quiddity of processes, and a shift from the ontological level of atomism to something that might be called a "black box theory" of chemical change.

Reduction to the Pristine State. There is ample evidence that the ground for this new perspective had been laid by the pragmatism and atheoretical attitude of metallurgists and iatrochemists. Imagine a goldsmith who during an alloying or reducing operation did not make the concept of substantial identity the very basis of his trade. However, such people were barely literate, and we do not know their theoretical suppositions about the connection between the material they were working on and its properties. Yet on the fringes of the learned tradition were a few noteworthy exceptions, among them Angelus Sala, an Italian who spent most of his life in Germany as a court physician, pharmacist, and adviser

[76] Magnenus, *Democritus reviviscens* (cit. n. 24), p. 197. Cf. the often-quoted definition, "mistio est motus corporum minimorum ad mutuum contactum, ut fiat unio," by Julius Caesar Scaliger, *Exotericarum exercitationum liber XV. de subtilitate ad Hieronymum Cardanum* (1557; Frankfurt, 1665), exerc. 101.1, p. 331.

[77] Sennertus, *De consensu et dissensu* (cit. n. 23), Ch. 12, p. 230; see also Gregory, "Studi sull'atomismo, II" (cit. n. 10), pp. 53–55. The second sentence, quoted here, however, points once more to the relational character of the notion *elementum*: something that is generated anew cannot, by definition, be the product of a re-solution. For us this conclusion is of course a tautology.

on commercial subjects. In his *Anatomia vitrioli* of 1609, which had to be translated from the vernacular since the author did not even know Latin, he described the formation and decomposition of copper vitriol pragmatically and to some extent also quantitatively. In doing so Sala distinguished, as usual, between transmutations, which occurred without major material additives and implied destruction of the old and emergence of a new substantial form, and changes that resulted from a mere juxtaposition or separation of finely divided particles. These latter processes were either *coniunctiones,* such as the alloying of gold and silver to yield electron or the apposition of particles of copper, acid, and water to yield vitriol, or *reductiones,* by means of which these little particles were reassembled into their former coherent state: "Reductio autem est operatio quaedam, per quam recolligimus et in unam massam coadunamus rem quampiam quae in minutissimas particulas dispersa et dilatata erat . . . et interim tamen *per Reductionem in pristinum suum statum et essentiam* revocatur et reducitur."[78]

The standard example was a solution of gold in *aqua regia* (a mixture of hydrochloric and nitric acids) and its precipitation using metallic silver. From Sala's account it is clear that he considered processes of this kind as mere divisions and rearrangements of metal atoms in which the metals retain their substantial identity, although "hidden" because of their dispersion into single atoms. As a practical chemist Sala did not bother with the nature of this "hiding" of qualities. Instead he accepted the reduction to its pristine metallic state as sufficient evidence for the persistence of "gold" throughout this process of dissolution and recovery. Even the delicate question whether gold in the form of *aurum potabile* retained its medical virtues and was therefore "real" gold—a much discussed topic at the time since potable gold was believed to be an almost universal medicine—was dismissed by Sala with the words that, instead of listening to the testimony of hundreds of authorities, one need only pay attention to the craftsmen: their expertise showed that gold could be recovered in its pristine form from such solutions without any damage to its qualities: "Possemus de hoc ipso vel sexcenta auctorum testimonia adducere, nisi magis adtenderemus ad id, quod agant isti artifices, quam quid loquantur. . . . si in manus experti artificis incidat, â spiritibus salium et sulphuris adpactis, liberari possit, et deinde pristinae suae formae, sine ulla qualitatum suarum laesione, restitui."[79] The naive corpuscularianism behind this conception of chemical change implied, however, that Sala regarded vitriol and all metal salts as mere aggregates of corpuscles, at the price of abandoning the idea of the homogeneity and substantiality of such compounds. At least from the chemical point of view this was a bit too simple, even for his contemporaries, and did not explain why properties of the atoms, such as their metallic character, disappear in the dispersed state and reappear when they are precipitated.

Hence Daniel Sennert, the learned professor of medicine, preferred to maintain the teleology of noble forms in order to account for the specific properties of the mixture. Expanding on Sala's corpuscular approach, Sennert conceived a

[78] Angelus Sala, *Anatomia vitrioli* (3rd. ed., Leiden, 1617), pp. 96–97 (emphasis added). On Sala see Hooykaas, "Discrimination" (cit. n. 74), pp. 646–648; and Hooykaas, "Experimental Origin" (cit. n. 1), p. 78.

[79] Angelus Sala, *Chrysologia seu examen auri chymicum* (Hamburg, 1622), 3.6.5, sig. K3r (on the "hiding"); and 2.1, sig [F6v–7r] (quotation).

more sophisticated argumentation, based on a great number of empirical observations of what he classified as reductions to the pristine state. The first types of examples referred to were simple distillations and sublimations of such substances as alcohol, sulfuric acid, and sulfur. Behind this was the assumption that sublimations in particular were merely mechanical operations—the chemists' pestle, as Sennert called them—by means of which bodies were mashed into their atoms.[80] Another and chemically more sophisticated argument for the atomic theory was taken from the reduction of different mercury compounds to running *mercurium vivum,* which retained its substantial form through all chemical and physical alterations.

> Mercurius praecipitatus si cum oleo tartari seu sale tartari per deliquium soluto teratur, sal, quod Mercurio adhaeret, unitur sali tartari, et Mercurium deserit, unde ille vivificatur. Ita si Mercurius sublimatus calci vivae misceatur, et Retortae indatur, sal vitrioli, et communis qui sublimatio inest, calci vivae adhaeret, atque ita argentum vivum in pristinam naturam redit et vivificatur; quomodo etiam cinnabaris in argentum vivum reducitur. . . . Et omnino quàm multas formas externas corpora naturalia cum aliis mista, salvâ manente formâ substantiali, induere possint, vel unus Mercurius docet, qui tot formas externas induit, ut meritò *πολύμορφος* dicatur. Mutatur in aquam limpidam, in liquorem butyro similem, sublimatur, praecipitatur, redigitur in pulverem, in vitrum, plumbi, auri, argenti, ut etiam laminari possit, figuram, et nescio quas alias formas induit; quas tamen omnes deponit, et pristinam ac nativam formam induit, si id quod ei admiscetur, ab eo separetur.[81]

To prove that there were indeed real atoms of mercury involved, and not just new substantial forms generated, Sennert mentioned an often-quoted observation from the nightmares of Paracelsian medication: ointments and fumigations with mercury, "in quibus argentum vivum in atomos redactum totum corpus penetrat," had the effect that a coin put in the patient's mouth became amalgamated —not to mention the findings of an autopsy.[82] In all these cases the reduction to the pristine state, *reductio in pristinum statum,* was the decisive criterion.

The same is true for another type of experiment presented by Sennert in order to prove that it was not the substantial form of a mixture that preserved the identity (*forma essentialis speciei*) of its compounds, but in fact the atoms themselves. He fused gold and silver together to obtain an entirely homogeneous alloy. Then he poured aqua fortis, or nitric acid, on it. The silver was dissolved, whereas the gold settled to the bottom as a finely divided sediment. He separated the two phases and precipitated the silver from the solution to yield another equally fine powder. Eventually, he melted each powder and obtained gold in the first, silver in the latter case.

> Etsi vero atomi illae sint minimae corpuscula: tamen in iis formae essentiales specierum integrae manent, ut modò dixi, et ipsa experientia testatur. Si enim simul aurum et argentum fundantur, atomi auri et argenti ita per minima miscentur, ut nullo sensu hae ab illis discerni queant. Interim utraeque suas formas integras servant. Quod vel ex eo patet, quòd, si massae isti aqua fortis affundatur, argentum solvitur, et

[80] Sennertus, *Hypomnema* 3.1.1 (cit. n. 23), p. 118 (reductions); and Sennertus, *De consensu et dissensu* (cit. n. 23), Ch. 19, p. 274 (pestle). A similar view was held by Berigardus, *Circulus Pisanus* (cit. n. 13), p. 422. At that time there was no unequivocal criterion to distinguish between simple and complex phenomena in chemistry.

[81] Sennertus, *Hypomnema* 3.1.1, p. 118.

[82] *Ibid.,* pp. 118–119.

> in liquorem abit, aurum verò formâ pulveris remanet. Argentum solutum si praecipitetur, formâ pulveris subtilissimi subsidet. Uterque pulvis, si seorsim fundatur, in pristinum aurum et argentum abit.[83]

All these experiments were of course not "invented" by Sennert, and it is even irrelevant whether he actually performed them. But he was the first to connect them systematically in order to use the *reductio in pristinum statum* as an argument in favor of atomism. It is interesting to see that Sennert, after having arrived at this conclusion in the *Hypomnemata physica* of 1636, had to revise his former ideas concerning the transmutation of metals.

Transmutation of Metals. Old and fairly well-documented evidence for metallic transmutation in fact existed, evidence that was apt to be used in defense of both the Aristotelian doctrine of substantial alteration and the alchemists' quest for gold. The facts were so plain that, as Sennert remarked, it would be a waste of time to argue about them. Several springs and rivers, especially in Smolník in Slovakia and near Goslar in the Harz Mountains, had the peculiar property that a piece of iron, on being immersed for some time, became true copper, first at the surface and later throughout. The same phenomenon could equally well be produced artificially by dipping an iron bar into a glass of water that contained blue vitriol. This process, called cementation, resulted in the transmutation of a vile metal into a nobler one. It had been known for a long time and described by authors whose credibility was beyond any doubt, such as Agricola, Libavius, and Cesalpino. Cementation was even known commercially for producing fine metallic copper—and is, by the way, still used today for the exploitation of low-grade ores and the recycling of scrap copper.[84]

There were, however, authors who doubted these observations and categorically denied the possibility of transmutation, among them the Lorraine physician Nicolas Guibert, writing in 1603. It is amusing to read how Sennert, in the 1629 edition of his *De chymicorum cum Aristotelicis et Galenicis consensu ac dissensu,* ridiculed Guibert's objections, and not because he was at that time still an Aristotelian, but because transmutation had been proved experimentally. It was the practical experience of metallurgists and assayers, accumulated over centuries, that Sennert introduced to support the view, contrary to Guibert's, that the copper produced by cementation was true copper and even of greater purity than that usually obtained from its ores. "Quasi per totum Imperium Romanum, fide publicâ, omniumque artificium et Docimastarum consensu non esset notissimum, cuprum illud genuinum esse, imò eo, quod multis in locis è terra effoditur, praestantius; et Guiberto, nescio quas ratiunculas in contrarium afferenti, plus

[83] *Ibid.*, p. 119. In another context the same process was also discussed by Scaliger in 1557 and Bodin in 1605; see Hooykaas, "Discrimination" (cit. n. 74), pp. 643–646.

[84] Sennertus, *De consensu et dissensu* (cit. n. 23), Ch. 2, p. 182; Georgius Agricola, *De natura eorum quae effluunt ex terra,* ed. Georgius Fabricius (Wittenberg, 1612), 2.10, p. 235; Agricola, *De natura fossilium,* ed. Georgius Fabricius (Wittenberg, 1612), 2.2, p. 701; Andreas Libavius, *Defensio et declaratio perspicua alchemiae transmutatoriae opposita Nicolai Guiperti* (Oberursel, 1604), pp. 216–233; and Andreas Caesalpinus, *De Metallicis libri III* (Nuremberg, 1602), 1.6, p. 17. For the commercial application see G. E. Löhneyss, *Bericht vom Bergkwerck* (Zellerfeld, 1617), IX, Bergordnung 5, p. 332, with reference to the Rammelsberg near Goslar. The pros and cons of transmutation appear at the beginning of Sennert's work under the heading *De veritate et dignitate chymiae,* the locus classicus for the defense of alchemy!

quàm tot artificum censurae et non unius saeculi experientiae, fidei habendum, et umbratilis ad pulpitum speculatio experientiae tot artificum praeferenda sit. Homine imperito nihil est ineptius!"[85]

But when the posthumous edition of Sennert's collected works was published, the editor added to this paragraph a note that he had found among Sennert's manuscript remains. In it Sennert admitted that the alleged transmutation was presumably a mere separation of copper from its vitriolic solution by means of iron ("videtur nimirum probabile, ferrum in aes non mutari, sed aes ex aquis vitriolatis saltem separari, ferri beneficio"), and he added that the reaction was equivalent to the one by which silver is precipitated from aqua fortis by means of copper. He correctly considered each process as an exchange of substances that retained their chemical identity and were, therefore, not transmuted. This view was also supported by the observation that from a given amount of natural or artificial vitriolic water only a certain amount of copper could be obtained. To explain this exchange Sennert suggested a mechanism whereby the "salt" that was "united" with copper in vitriolic water tried to "dissolve" the iron that had been added. In doing so it released the copper atoms with which it had been "united" until then, and these atoms, abandoned by the "salt," sank to the bottom, where they could be collected: "Nimirum dum cuprum in aqua salsa solutum est, si iniiciatur ferrum, tum sal illud, quod est in aqua, etiam ferrum solvere conatur, et aggreditur, atque ita atomos cupri, cum quibus se univit, deserit, quae à sale derelictae, ad fundum descendant, quod praecipitari dicitur."[86]

From his account it is evident that Sennert's change of mind was due to his conversion to atomism. Indeed he referred to the appropriate passage in the *Hypomnemata physica*. Sennert even went a step further and conceived an experiment by which one could prove that the process of cementation was truly quantitative: one ounce of copper was dissolved in sulfuric acid to obtain an acid, blue solution of copper vitriol. Then two ounces of iron filings were added. The vessel was kept in a warm place until all of the iron had disappeared, the blue solution turned colorless, and a red precipitate settled at the bottom. This precipitate was washed, dried, and reduced, to yield exactly one ounce of copper—"quantum scilicet solutum fuit"—the same amount that had been dissolved before.[87]

Again the method of *reductio in pristinum statum* was applied to demonstrate the existence of atoms. Sennert was thus able to avoid the difficulties involved in explaining what happened to the properties of the metal when it "united" with

[85] Sennertus, *De consensu et dissensu* (cit. n. 23), Ch. 2, p. 182. For Guibert see Partington, *History of Chemistry* (cit. n. 16), Vol. II, p. 268.

[86] Sennertus, *De consensu et dissensu,* Ch. 2, p. 182. The addition seems to appear first in the edition Frankfurt/Wittenberg 1653; in the corresponding paragraph of the last edition he supervised—Daniel Sennertus, *De chymicorum cum Aristotelicis and Galenicis consensu ac dissensu* (Wittenberg, 1629), pp. 10–11—Sennert still displayed his belief in transmutations.

[87] Sennertus, *De consensu et dissensu,* Ch. 2, p. 182. From Sennert's account it is not entirely clear whether he in fact performed this experiment, for he went on to say that one evaporates the remaining liquid to dryness and finds exactly two ounces of vitriol, corresponding to the two ounces of iron added. The correct value, however, would be almost 10 ounces $FeSO_4{\cdot}7\,H_2O$, 6 ounces $FeSO_4{\cdot}H_2O$, or 5½ ounces $FeSO_4$, depending on the degree of heat applied in drying the residue. Since we have no manuscripts, it is difficult to judge what Sennert actually did or wrote. In my opinion, the most likely explanation would be that he was so exclusively concerned with the *reductio in pristinum statum* that only in the first part of the reaction did the quantitative side seem relevant to him, whereas the rest may have been added somewhat negligently in order to complete the balance of substances. It is unreasonable to assume either that the famous iatrochemist was unaware that iron metal cannot be reobtained by this process, or that he simply mixed up iron and green vitriol.

Figure 2. *Joachim Jungius (1587–1657). Courtesy of the Smith Collection and the Beckman Center.*

the "salt" in the solution, or whether the particles of copper, salt, and water form an essentially uniform mixture (as required by chemical experience) or a mere juxtaposition of parts (as imagined by Sala).

Sennert was presumably not aware that in 1630 Joachim Jungius had reached a similar conclusion.[88] Jungius's approach, however, was different. He neither took the *reductio ad pristinum statum* as the decisive criterion nor concerned himself with the quantitative aspect of cementation. He correctly observed that it was an exchange of material and by no means a transmutation, because, during the process, the color of the solution gradually changed from blue to greenish—the color of the iron vitriol—and once all the dissolved copper had been consumed, no further iron was "transmuted" ("ubi tantum aeris, quantum in se continuit, rursus exspuit, ferrum amplius ita transmutari nequit"), since with green

[88] The chronology is not entirely sure, but it is reasonable to assume that the posthumously added paragraph from *De consensu et dissensu chymicorum* was written after the *Hypomnemata* of 1636. Since Jungius's ideas of 1630 were not published until 1661, and Sennert died in 1637, it is unlikely that there was any mutual influence in this area.

vitriol alone, the reaction would not take place. However, Jungius's point of view was different from Sennert's, as was his experimental technique. Whereas Sennert used an acid solution that slowly dissolved the iron, Jungius obviously referred to a neutral solution in which the process was not accompanied by simultaneous dissipation of the metal by the acid. Hence the iron objects Jungius dipped into the solution did not disappear but retained their original form. Taken out after a while, they were covered with a layer of copper, so that one could carefully pull the iron out of the copper sheath.

> Bacilla ferrea in aquis caeruleo vitriolo praegnantibus ita aere quasi vestiri, ut ferrum ex eo tanquam è vaginâ educi possit; verum etiam clavos et hujusmodi alia ferramenta in puteis aquâ hujusmodi plenis temporis diuturnitate tandem aerea inveniri. Nulla tamen hic transmutatio intervenit, sed permutatio potius. . . . Quodsi id sensim fiat et longo temporis spatio atomis aeris in locum atomorum ferri subeuntibus aliquando potest, ut ferramenta eandem figuram servantia aerea tandem inveniantur.[89]

The explanation suggested by Jungius was a corpuscular one: the copper atoms exchanged places with the iron atoms. Were it not through an exchange of tiny atoms, one atom taking exactly the space its counterpart had just occupied, it could not be understood why the external form of the metal was completely retained during the process. For the gross form of an object, such as the form of a nail, was of course entirely fortuitous and could therefore exert no formative power whatsoever. Jungius's argument came more from a topological or crystallographic point of view than from a chemical one. The only quantitative statement we meet in his account—"spiritus sulfuris . . . aes . . . à se dimittit et tantumdem ferri vicissim complectitur et quasi deglutit"—seems to suggest a one-to-one exchange of atomic positions.[90]

Other scholars of Jungius have interpreted this same passage entirely differently, namely, as a quantitative statement. But this has led them into severe difficulties, which the interpretation offered here may avoid.[91] In addition there is another argument in favor of the mere spatial or topological sense of Jungius's *tantumdem*.[92] The original manuscript, written around 1629/30, reads only *tantumdem ferri rursus deglutit,* whereas the additional *vicissim complectitur* came in when Jungius first dictated the text shortly afterward. *Vicissim complectitur,* however, seems an indication that he wanted to put more stress on the spatial

[89] Jungius, *Praelectiones physicae* (cit. n. 11), p. 234, lines 20–21, 3–17 (longer quotation).

[90] *Ibid.,* p. 234, lines 7–13. The passage reads: "Nam spiritus sulfuris, qui hospitium habet in aquâ istâ, quia vel promptius ferrum ut imperfectius metallum quam aes corrodere et, ut ita loquar, perdomare potest, vel quia majore sympathia erga illud afficitur, aes qod hactenus insedit, cum quo hactenus in mistum sive, ut Chymici loquuntur, magisterium coaluit, à se dimittit et tantumdem ferri vicissim complectitur et quasi deglutit."

[91] Emil Wohlwill, *Joachim Jungius und die Erneuerung atomistischer Lehren im 17. Jahrhundert: Ein Beitrag zur Geschichte der Naturwissenschaft in Hamburg* (Abhandlungen aus dem Gebiete der Naturwissenschaften X, 2) (Hamburg, 1887), p. 58; Kangro, "Erklärungswert" (cit. n. 1), pp. 32–33; and Walter Pagel, "Chemistry at the Cross-Roads: The Ideas of Joachim Jungius," *Ambix,* 1969, *16*:100–108, on p. 103. Kangro, *Joachim Jungius* (cit. n. 20), pp. 85–86, tried to save Jungius's quantitative methodology by assuming that he was thinking in terms of atomic volumes.

[92] Jungius's famous disciple Bernhard Varenius interpreted it spatially in *Geographia generalis* (1650), 2nd ed., ed. Isaac Newton (Cambridge, 1681), 1.17.11, p. 199: "Cupreae aquae particulae in ablatarum ferrearum locum reponuntur sive ibi haerent, dum allabuntur cum fluente aqua." However, the idea was not developed any further and seems unrelated to similar seventeenth-century ideas about the formation of crystals; see also Emerton, *Scientific Reinterpretation* (cit. n. 8), pp. 126–153.

aspect, the one-to-one exchange of atomic positions that were surrounded by neighboring positions—a process that he must have considered as something rather unusual and unlike other transmutations. In fact, in his first draft of the text he called it *metamorphosis* (a change by *translocatio partium*), a term that does not appear elsewhere in this work.[93]

The Range of Chemistry. Taken together, the chemical evidence presented by various authors to support the corpuscular view of matter supplied good empirical reasons for regarding natural bodies as divisible into much smaller ones that somehow retained their specific properties and could frequently be recombined to yield the original body. It is not surprising that most experiments proposed in that context referred to metals, metal salts, their aqueous solutions, and mineral waters. There are both chemical and historical reasons for this choice. Metals and salts were the best-known classes of substances, easy to obtain, fairly easy to treat by well-established laboratory techniques, and simple enough to fit into a crude theoretical framework. Among them the noble metals gold, silver, copper, and mercury occupied the most prominent place since their compounds could most easily be reduced to the respective metal and thereby identified. On the other hand there was a great interest in mineral waters, stemming from late sixteenth-century Paracelsianism. Within the iatrochemical tradition the analysis of natural mineral waters became a prominent branch of medical chemistry and was in fact the driving force behind the development of modern chemical analysis. For this *via humida* new experimental techniques were required that had not been available to the traditional *via sicca,* the "dry" analysis by means of fire.[94] The outstanding example of this new orientation is Robert Boyle's *Sceptical Chymist* of 1661, with its harsh attack on the use of fire in chemical analysis.

Yet the range and depth of experimental proofs for the atoms as such remained limited. The old experiments were more frequently referred to in writing than repeated or extended in the laboratory. During the first half of the seventeenth century attempts to widen the experimental basis were exceptional and hardly convincing, not even for contemporaries. Most of these attempts appear as rather tentative excursions from the better-established field of inorganic chemistry into the vegetable and animal kingdoms, mounted more or less for the sake of comprehensiveness and in order to display the universality of the corpuscular hypothesis. Sennert's treatment is symptomatic in this regard. After a lengthy presentation of chemical proofs in favor of the atoms he went on to argue that not only inanimate bodies were composed of atoms but also "some" animate bodies: "imò dantur atomi non solùm corporum inanimatorum, sed et animatorum quorundam"; atoms that were apt to carry, retain, and propagate the *anima,* the substantial form of a living body. Sennert was thinking of the seeds of plants and

[93] In a later revision of the manuscript Jungius replaced *metamorphosis* by *transmutatio;* see Jungius, *Praelectiones physicae* (cit. n. 11), p. 234, lines 24–26. *Transmutatio* was Jungius's general term for substantial alterations—be they by *syncrisis,* by *diacrisis,* or by rearrangement of particles; see *ibid.,* p. 70, line 24–p. 71, line 7.

[94] Allen G. Debus, "Fire Analysis and the Elements in the Sixteenth and the Seventeenth Centuries," *Ann. Sci.,* 1967, *23*:127–147. See also Gernot Rath, "Die Mineralquellenanalyse im 17. Jahrhundert," *Sudhoffs Arch.,* 1957, *41*:1–9; Allen G. Debus, "Solution Analyses prior to Robert Boyle," *Chymia,* 1962, *8*:41–61; and Noel G. Coley, " 'Cures without Care': 'Chemical Physicians' and Mineral Waters in Seventeenth-Century English Medicine," *Medical History,* 1979, *23*:191–214.

the sperm of animals, but also of spontaneous generation.[95] However, the indications of corpuscular structure in animate matter that Sennert presents are brief, conventional, and disappointing: the growth of tartar crystals in an entirely clear wine; the presence of chalk crystals in arthritic joints; the transmission of diarrhea to a suckling child whose mother had drunk milk from goats fed on laxative herbs; and finally the inhomogeneity of milk, blood, and bones. Sennert even includes the rather misplaced standard reference to the *acari,* which Aristotle had taught as being the smallest existing animals.[96]

In this context it would be worthwhile to compare the experimental approach of the early seventeenth-century "chemical" atomists with that of Robert Boyle. In Boyle's experiments "organic" material occupied a central place. In the "historical part" of his *Considerations and Experiments,* where the experimental background for his corpuscular philosophy was most fully presented, the first four "observations" were in fact experiments with animal and vegetable bodies: the development of a chicken in an egg, the growth of plants in sealed glass containers, the engrafting of a scion onto another plant, and the decay of a rotten cheese. All of these examples were aimed at demonstrating that qualitative change could occur in closed systems without any material additive and must therefore be explained by a change of texture within the corpuscular structure of matter. The corpuscles themselves, however, were taken for granted. The same applies to Boyle's subsequent ten "experiments," most of which were carried out with inorganic material. Their aim was to show how, by means of mechanical operations, the internal texture of a body could be altered and, by this means, a change of qualities and even true transmutations effected. Only the first experiment bears some resemblance to traditional "proofs" for the atoms. White camphor was dissolved in sulfuric acid to yield a reddish solution that lacked the characteristic smell of camphor. On addition of an excess of water, however, "the camphire that lay concealed in the pores of the menstruum, will immediately disclose itself, and immerse in its own nature and pristine form."[97] Yet Boyle's interpretation differed notably from the conventional one based upon the *reductio in pristinum statum.* In his opinion this cyclic process was meant to be a proof neither for the existence of imperceptible camphor corpuscles nor for their reception into the vacua of the liquid, which was taken for granted. For Boyle the experiment was an illustration of how mechanical action, such as dissolution, could alter heaviness, color, transparency, odor, fixity, and volatility of bodies because their intrinsic texture was altered. The properties of a body were seen as mechanical responses to outside objects and not as innate qualities whatsoever.

[95] Sennertus, *Hypomnema* 3.1.1. (cit. n. 23), p. 119. All of this is dealt with in great length in the subsequent *Hypomnemata,* IV ("De generatione viventium") and V ("De spontanea viventium generatione") (1636), in Sennert, *Opera* (cit. n. 23), Vol. I, pp. 123–172.

[96] Aristotle, *Historia animalium* 5.32 (557b8); and Sennertus, *Hypomnema* 3.1.1, p. 119.

[97] Robert Boyle, *Considerations and Experiments touching the Origin of Qualities and Forms* (1666), in *The Works of the Honourable Robert Boyle,* ed. Thomas Birch, 6 vols. (London, 1772), Vol. III, pp. 66–112, esp. pp. 76–112; quoting p. 76. Boyle's rendering of the camphor experiment is, by the way, quite correct. At room temperature camphor is easily soluble in sulfuric acid and can be precipitated again by means of an excess of water. The colors mentioned by Boyle, however, were evidently due to an impurity; see Thomas Stewart Patterson, E. F. M. Dunn, C. Buchanan, and J. D. Loudon, "The Rotation-Dispersion of Camphor, Camphoroxime, iso-Nitrosocamphor, and Oxymethylene Camphor," *Journal of the Chemical Society* (London), 1932, *134*:1715–1747, on pp. 1719–1721.

The difference between Boyle's mechanical corpuscular philosophy and the earlier "chemical" atomism is evident.

VI. CONCLUSION

It is difficult to believe that empirical arguments of the six types analyzed here were enough to convince those who did not already share the atomic view of matter. But since atomism was still a controversial issue, and its adherents maintained that it was rooted in experience, why then did they not devote much more effort to widening and strengthening the empirical basis? After all, there was little truly conclusive evidence in favor of the atoms that could not have been easily dismissed from a Peripatetic or Neoplatonic point of view. Writing in the 1660s even Boyle had to concede that "the intelligible [i.e., corpuscular] philosophy, . . . seems hitherto not to have so much as employed, much less produced, any store of experiments."[98]

As a matter of fact, the mere extrapolations from the visible to an underlying invisible reality were epistemologically questionable, to say the least. The phenomena of distillation, evaporation, growth of crystals, and so on, were appropriate for showing that something material was transferred from one place to another, but they did not prove its corpuscular nature. In addition, in almost all of these cases the experiences referred to were little more than variations on classical themes. Even when true experiments were carried out, they were often merely practical performances from a common repertory of literary paradigms. The corpuscular theories of light, magnetism, and electricity echoed the *ἀπορροαί* and *ἀποφορά* of Greek medicine without new experimental support. The corpuscular interpretation of rarefaction and condensation remained questionable, since the entire problem of how the atoms interact and cohere was open. The introduction of a material ether disposed of these difficulties while creating new ones by the strange hybridization of particulate and continuous matter. As far as experimental support for the corpuscular theory was concerned, the chemists and iatrochemists offered indeed the most convincing, yet still inconclusive arguments, based, to some extent, upon new facts, new techniques, and new methodologies.

By its very nature the chemical approach was pragmatic, realistic, and eclectic. The majority of chemists worked on real matter and real properties in a purposeful way. After all, they wanted to sell a product or to cure a patient. They simply could not afford to rely too closely upon a rigid theory. Needless to say, contrary to a stubborn historiographical myth, Boyle's clockwork universe "proved a sterile and occasionally adverse intellectual climate for an understanding of the processes underlying chemical change."[99] Hence it was not the mechanical philosophy that was to succeed in chemistry, but a noncommittal, substance-oriented notion of the corpuscle as something closer to an elementary particle or a small amount of substance, corresponding to something real in the chemists' vessels and furnaces and endowed with sensible properties. Jungius's

[98] Robert Boyle, "A Physico-Chymical Essay, containing an Experiment, with some Considerations touching the differing parts and redintegration of Salt-Petre," in *Certain Physiological Essays* (1661), in *Works,* Vol. I, pp. 359–376, on p. 375.

[99] Kuhn, "Robert Boyle" (cit. n. 5), p. 15; see also Boas, "Mechanical Philosophy" (cit. n. 1), pp. 494–499.

Figure 3. Robert Boyle (1627–1691). Courtesy of the Smith Collection and the Beckman Center.

maxim "si sensilia principia sufficiunt, quid opus est insensilia insuper sensilium rerum principia adsciscere?" epitomized a widely shared attitude.[100]

As in Baconian science, truth was not an ontological category but a social one, confirmed by utility; similarly, the undetermined atoms of the chemists were merely useful means for practical and explanatory ends, at best compatible with the experimental results, though not derived from them. Empiricism and realism were to prevail over the philosophically consistent atomism of the late seventeenth century. By the standards of Boyle's mechanical philosophy and John Locke's insistence on the epistemological status of the corpuscles, there was nothing of its kind in the eighteenth century. The new interest focused on elements and affinity, not on atoms and motion.[101] Authors of chemical textbooks relegated the corpuscular theory of matter to the introductory chapters of their works and had little recourse to it when they discussed the properties of sub-

[100] Jungius, *Praelectiones physicae* (cit. n. 11), p. 100, lines 11–13.

[101] Peter Alexander, *Ideas, Qualities and Corpuscles: Locke and Boyle on the External World* (Cambridge/London/New York: Cambridge Univ. Press, 1985); Boas, "Mechanical Philosophy," pp. 505–520; and Arnold Thackray, *Atoms and Powers: An Essay on Newtonian Matter-Theory and the Development of Chemistry* (Harvard Monographs in the History of Science) (Cambridge, Mass.: Harvard Univ. Press, 1970).

stances and the operations of chemistry. The particles were taken for granted, and their ontological and epistemological status did not even become a matter of debate. This noncommittal character enabled the resulting notion of corpuscle to assume whatever requirements future research would find convenient. The requirement of decisive proof or falsification by means of experiments and, what is more, the very question of the truth-value of the corpuscular view of matter were dismissed in favor of a merely operational link between theory and reality.[102]

It is not yet entirely clear by what exact mechanism the corpuscular theory, despite the obvious lack of experimental support, was able to win so many adherents among those who considered themselves empirical scientists after only a few decades of vigorous pros and cons. In any case, it would be mistaken to describe the steep rise of atomism as "a triumph of patient experimental research over metaphysical speculation,"[103] unless we admit that science proceeds by inferring correct theories from inadequate experiments. The acceptance of corpuscularianism cannot be reduced to a single cause, and least of all to the experimental progress of science alone. The arguments and rhetorical stratagems in defense of atomism operated, as we have seen, on many different levels simultaneously. They came from epistemological, mathematical, and empirical points of view, not to mention the theological and metaphysical ones. Their stratification, interdependence, and respective momentum need further study. The aim of this study was but to evaluate the more empirical grounds. They were rooted in the common heritage of ancient natural philosophy, but they also incorporated new experiences from the crafts tradition. Among them three lines of argumentation were especially powerful: (1) the new visual approach to reality, enabled by the recently invented microscope and based upon the bold hope that truth might be made visible by extended technical effort; (2) the readiness of practicing chemists and metallurgists to take material objects as a reality that needed no further ontological determination; and (3) the persuasive appeal of the pictorial scheme supplied by Lucretius's poetic imagery, which offered an immediately convincing way of picturing material processes on the basis of everyday experience within the visible world.

[102] Robert Boyle, *About the Exellency and Grounds of the Mechanical Hypothesis* (1674), in *Works* (cit. n. 97), Vol. IV, p. 77.

[103] Hooykaas, "Experimental Origin" (cit. n. 1), p. 79.