# Preface

Dol: *Are you sound?*
*Have you your senses, masters?*
Face: *I will have*
*A book, but barely reckoning thy impostures,*
*Shall prove a true philosopher's stone to printers*

Sub: *I have another work, you never saw, son,*
*That three days since past the philosopher's wheel,*
*In the lent heat of Athanor; and's become*
*Sulphur of Nature*

Ben Johnson (1573–1637), The Alchemist, 1612

## A Few Words about What, Why, and How

A scientific theory is not a holy writ and sacred cows are routinely slaughtered in science. But do not hold this against science. On the contrary, it represents the perpetual struggle to reach the ultimate truth and understanding. As more details are discovered and experiments refined, scientific theories are improved or even revolutionized. And the theory of the synthesis of the chemical elements is no exception.

Recent discoveries in astrophysics set the amount of matter in the Universe, at least, matter of the kind we are familiar with, at around 4%. About 24–25% of the mass in the Universe is in the form of what is called 'dark matter', while the rest comes under the heading of 'dark energy'. Dark matter does not emit detectable photons and this is the reason for the annoying name. But in this book we shall discuss only the chemical composition of the visible matter. Visible means that it emits photons and can be seen or detected directly, by us. However, dark matter and energy affect our subject indirectly by influencing the formation of galaxies, and hence the formation of the first stars. A short digression into galaxy formation will thus be presented, to set the scene for those early stars.

In recent years we have witnessed a reversal in the line of research: from a quest for the formation of the chemical elements, how they came about, and why, the research has turned into attempts to understand what the various compositions tell us about the structure of the Universe. The change came about when attempts to explain the formation of the elements required hypotheses concerning global structure, in contradistinction to the investigation of pure nuclear physics processes and the way they lead to the synthesis of chemical elements.

Apart from a source of energy, everything needed for life can be obtained from this 4% of matter which is composed of ninety chemical elements found on Earth.

Two elements, technetium and promethium, are not found on Earth, while technetium is found in stars. On Earth, there are about 272 stable nuclei and 55 naturally occurring radioactive isotopes. This book describes how these elements were formed and where, how our understanding of their formation has evolved, and what the various compositions imply.

The question as to what constitutes a scientific discovery and who should be credited for it, or even when a discovery can be defined as such, does not have a definite answer: is it the first to make the discovery but is not believed, or is it the person who comes in at the end and clinches things? Is it the first who wrote the expression with an undefined constant or the one who took the new expression and fixed the constant? We are not going to answer this philosophical question, but instead attempt to describe how the idea has evolved up to the present day, identifying those who contributed to it, and conjecturing about what may happen tomorrow.

Element synthesis was born as a by-product of the problem of the energy source in stars. With the birth of nuclear astrophysics and the explanation of stellar energy sources came the saga of element synthesis in the stars. From its beginnings as a goal in itself, it soon turned out that the synthesis of the elements is intertwined and entangled with many fundamental processes in the cosmos. Today, element synthesis and nuclear astrophysics no longer stand alone, but are part of global processes that take place in galaxies, from galaxy formation and galaxy–galaxy collisions to mixing processes in galaxies and stars. Hence, as the title indicates, there is no question now of nuclear astrophysics remaining in splendid isolation. A global view is beginning to emerge, and it is the emergence of this panoramic picture which we shall try to depict and detail in this book.

It is not obvious that mankind will draw any practical benefits from knowing how the elements were formed. I find it appropriate at this point to cite what Roscoe[1] wrote in 1862, in his introduction to the papers by Kirchoff and Bunsen on spectroscopy, a discipline so essential for our subject here:

> It is unnecessary to insist, at the present day, upon the incalculable value of discoveries in the natural sciences, however abstruse they may be, or however far-distant may appear their practical application. If we put aside for the moment that highest of all intellectual gratifications afforded by the prosecution of truth in every form, the perception of which is one of the chief distinctions of humans from brute life, and if we look to the results of scientific discovery in benefiting mankind, we find so many striking examples of the existence of truths apparently altogether foreign to our everyday wants, which suddenly become points of great interest to the material prosperity and the moral advancement of

---

[1] Roscoe, H.E. Edinburgh Review, No **CXVI**, 295, (1862). *Researches on the Solar Spectrum, and the Spectra of the Chemical Elements* by Kirchoff and *Chemical Analysis by Spectrum Observations*by Bunsen and Kirchoff, Pogg. Annal. translated by Roscoe. Sir Henry Roscoe was a PhD student of Bunsen in Heidelberg, working on photochemistry, and in particular determining the effect of light on the reaction $H_2 + Cl_2$. This research led Bunsen to carry out the first attempt to estimate the solar constant, or as he called it, the radiant energy of the sun. However, this Bunsen–Roscoe collaboration was terminated abruptly by Bunsen when he discovered the power of spectroscopy and devoted all his time to it.

> the race, that we are less apt to utter the vulgar cry of 'cui bono' respecting any scientific discovery; and if we are not advanced enough to love science for the sake of her truth alone, we at least respect her for the sake of the power she bestows. [ ... ] A great discovery in natural knowledge, for which no equivalent in direct benefit to mankind has as yet been found, but which nevertheless excites our liveliest interest and admiration, has lately been made in the rapidly advancing science of chemistry. [ ... ] This is so delicate in nature, that, when applied to the examination of the substances composing our globe, it yields most new interesting, and unlooked-for information. At the same time it is so vast an application as to enable us to ascertain with certainty the presence in the solar atmosphere—at a distance of 95 000 000 miles—of metals, such as iron and magnesium, well known on this Earth, and likewise to give us good hopes of obtaining similar knowledge concerning the composition of the fixed stars. Here, indeed, is a triumph of science! The weak mortal, confined within a narrow zone on the surface of our insignificant planet, stretches out his intellectual powers through unlimited space, and estimates the chemical composition of matter contained in the Sun and the fixed stars with as much ease and certainty as he would do if he could handle it, and prove its reaction in the test tube. [ ... ]
>
> How did two German philosophers, quietly working in their laboratory in Heidelberg, obtain this inconceivable insight into the process of creation? Are the conclusions which they have arrived at logical consequences of bona fide observations and experiment—the only true basis of reasoning in physical science—or do they not savour somewhat of that mysticism, for which our German friends are famous? Such questions as these will occur to all who hear of this discovery.

Roscoe went on to point out that:

> The further we penetrate into the secrets of nature, the more we find there remains to be learnt.

This is also the motto of this book about the chemical elements, a century and a half after spectroscopy was discovered as a tool. Indeed, not only was Roscoe's vision found to be correct, but it went well beyond expectations, and today, in retrospect, we can better appreciate his profound understanding. The present book is about just this.

The title of the book and the idea of 'element genesis' appeared for the first time in 1934, when the chemist Lewis (1875–1946)[2] suggested that a major part of the matter in the Universe might be composed chiefly of iron and nickel, like metallic meteorites. The idea was based on the fact that such a material is thermodynamically stable with respect to all spontaneous transmutations, except for very high temperatures. Lewis hypothesized that the bombardment of such a material by cosmic rays could generate all the elements seen in the crust of the Earth. Lewis claimed that the relative abundance of the main atomic species indicates 'a genetic relationship' between the cosmic rays and the crust of the Earth. The explicit idea that the elements are created by some cosmic physical process is probably due to Lewis, but present day views about the mechanisms have changed completely. It is the evolution of these ideas into present day thinking that will form the subject of the present book.

---

[2] Lewis, G.N.: *The genesis of the elements*. Phys. Rev. **46**, 897 (1934)

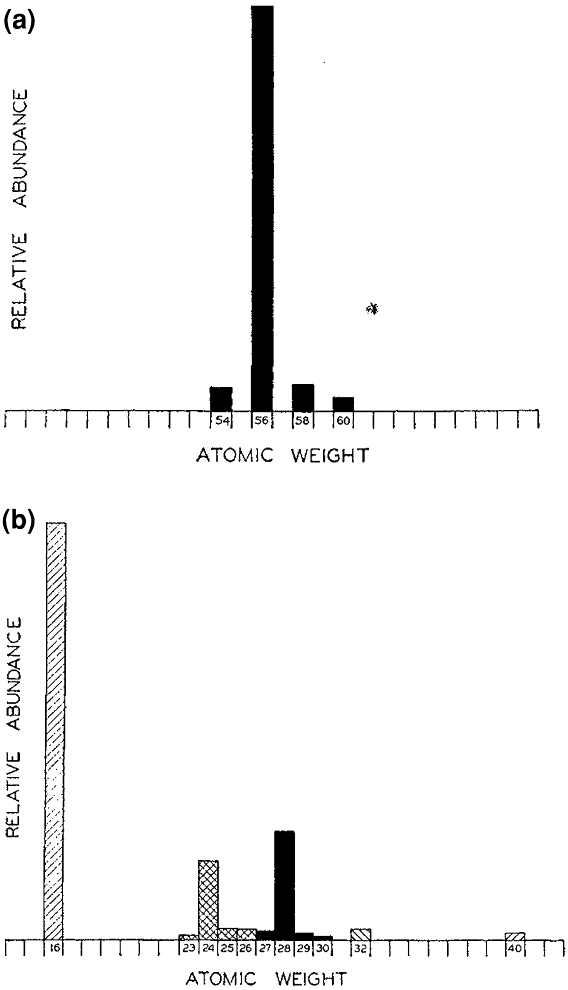


**Fig. 1** The first attempt to hypothesize about the genesis of the elements as a result of bombardment of iron and nickel by cosmic rays. **a** Relative abundances of the major constituents of metallic meteors. **b** Relative abundances of the major constituents of stony meteors. Both panels give abundances as a function of atomic weight. After Lewis' paper 1934

For centuries scientists looked for ways to transform the chemical elements from one to the other, and in particular to produce gold out of sand. Stars materialize this long-standing dream of the alchemists, since they synthesize heavy elements out of lighter ones and thus create the chemical elements we see today. All chemical elements heavier than carbon (including carbon) were synthesized at some time in the past inside the hot cores of massive stars. The elements were removed from the furnace either by an explosion or a slow mass loss from the star.

So the process has two phases: synthesis deep within a star and removal into interstellar space without destruction. Chemical elements are a by-product of stellar energy sources which drive the cosmos.

The idea of element transmutation, which can be traced back to the Greek philosophers, prevailed amongst alchemists of the Middle Ages. People like Magnus, Bacon, and Vincent of Beauvais firmly believed in its feasibility. Such ideas about the transformability of matter were advocated even well into the seventeenth century, at least from the academic point of view. Among those who upheld them we find Newton and Leibniz, although they did not have a shred of evidence that this was really possible. This book describes the evolution of our ideas about the synthesis of the elements from the beginning right up to the present day, along with the controversies, discussions, and failures. Dramatic progress has been made in the past 80 years, but many problems remain. So this book will not be the 'last word'. The field is still evolving and represents an active field of research, promising many more surprises in the future.

Leading scientists are frequently immortalized by naming a lunar crater or a mountain after them. When this happens, the year of their death is followed by a small m.

Haifa, February 2011 Giora Shaviv

Springer

http://www.springer.com/978-3-642-28384-0

The Synthesis of the Elements
The Astrophysical Quest for Nucleosynthesis and What It Can Tell Us About the Universe
Shaviv, G.
2012, XXII, 684 p. 255 illus., 117 illus. in color.,
Hardcover
ISBN: 978-3-642-28384-0