Handbook of Isotopes in the Cosmos

Hydrogen to Gallium

Each naturally occurring isotope has a tale to tell about the history of matter, and each has its own special place in cosmic evolution. This volume aims to grasp the origins of our material world by looking at the abundance of the elements and their isotopes, and how this is interpreted within the theory of nucleosynthesis. Each isotope of elements from hydrogen to gallium is covered in detail. For each, there is an historical and chemical introduction, and a table of those isotopes that are abundant in the natural world. Information given on each isotope includes its nuclear properties, solar-system abundance, nucleosynthesis in stars, astronomical observations, and isotopic anomalies in presolar grains and solar-system solids. Focussing on current scientific knowledge, this *Handbook of Isotopes in the Cosmos* provides a unique information resource for scientists wishing to learn about the isotopes and their place in the cosmos. The book is suitable for astronomers, physicists, chemists, geologists and planetary scientists, and contains a glossary of essential technical terms.

DONALD CLAYTON obtained his Ph.D. at Caltech in 1962, studying nuclear reactions in stars. He became Andrew Hays Professor of Astrophysics at Rice University, Texas. In 1989 he moved to Clemson University, South Carolina, where he became Centennial Professor of Physics and Astronomy in 1996. Clayton has received numerous awards for his work, including the Leonard Medal of the Meteoritical Society in 1991, the NASA Headquarters Exceptional Scientific Achievement Medal in 1992, and the Jesse Beams Award of the American Physical Society in 1998. Clayton is a fellow of the American Academy of Arts and Sciences. He has published extensively in the primary scientific literature, and has written four previous books and published on the web his Photo Archive for the History of Astrophysics.

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Donald Clayton
Frontmatter
More information

Contents

Illustrations

Atomic number, Z, plotted against neutron number, N, for:

Stable natural isotopes are outlined solidly, whereas those few radioactive isotopes which have natural observable abundances in astrophysics have dashed outlines.

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Preface

This book concerns the common atoms of our natural world. How many of each element exist, and why? What variations are found in the relative numbers of the isotopes of each element, and how are those variations interpreted? If I could write an epic poem, I would lyricize over the history of the universe writ small by their natural abundances. I would rhapsodize over the puzzling arrangements at different times and places of the thousand or so different isotopes of some ninety chemical elements. These different arrangements speak of distant past events.

My more prosaic approach is to consider the elements one by one. For each chemical element I first introduce some properties, perhaps chemical, perhaps poetic, perhaps cultural. Few today know the elements, and fewer can choose to read a chemistry textbook to find out. Each element introduction is followed by an account, isotope by isotope, of the isotopic abundance and its measured variations, how these may be accounted for on the basis of the nucleosynthesis theory, and of the cosmochemical implications for interstellar dust and for the origin of the solar system. These have inspired my scientific life. So penetrating are their clues that the proliferation of isotopic connections smacks of a hard rain on the face – bracing, daunting, overwhelming, refreshing. That is how I want the reader to experience the isotopes, because that is what they are to me.

This element by element consideration is preceded by an introductory essay styled less technically for general readership. At the end of the book I place a **Glossary**. It describes the meanings of concepts that are used repeatedly in the story of the isotopes. In the **Glossary** I have taken pains to be technically correct without any burden of appearing to be overly technical. I try to explain these building blocks of the science as I would in conversation with any science-educated person. One might read the **Glossary** prior to reading about a specific isotope – but not necessarily so. My goal is a communication that can be opened at any point and simply read. I envision readers who will, as the spirit moves, open the book to any point and be able to read of a wondrous world. The reader will decide which concepts of the **Glossary** s/he needs.

Some may criticize my omission of references to the research literature; their inclusion is so traditional for scientists. But to include them would detract from my goal. I imagine instead a conversation between learned people. If on a dining occasion I relate, to a physician, say, my astonishment that one can collect from the meteorites huge numbers of small rocks that are older than the Earth, he will usually be hooked by curiosity. He will want to know how I can say that, but he will not want to hear, "You must read Zinner *et al.* in the 1996 *Astrophysical Journal*. I can give you the reference." Intellectual discourse relies on the ability to relate discoveries and the reasons for their interpretation. Nor would things be different if my conversation were with a nuclear chemist. Our identities might conveniently allow us to assume some common knowledge, but he still will want to hear, "What is known? How is it known? Why should I care?"

This book is therefore not offered as a handbook of technical detail. Such a book, admirable though it would be, would be replete with references to the journal papers that have discovered and interpreted the facts. So rich are the isotopic phenomena that even practicing isotope scientists are hard pressed to commit their riches to instant recall. Four decades of research leave me totally preoccupied with the natural manifestations of the abundances of the isotopes. My aim is to share my own fascination at those discoveries. To lend appreciation of the immense fabric of natural philosophy is the goal. Technical details appear throughout because understanding requires them. Readers will appreciate the issues hanging on the isotopic abundances by reading of them. Clues to the origins of nuclei lie hidden in the manifestations of their abundances. My aim is to grasp the origins of our material world. This might be likened to the viewing of a great painting, which is clearly much more than the countless technical details of the brushstrokes. My topic is the painting, not its brushstrokes.

Many scientists see need for a readable companion to the isotopes. One wants not so much the nuclear data characterizing each isotope, for which large data bases of nuclear physics exist, and for which web sites will allow you to download more than one ever wants to know. One often wants just to experience directly the natural history that the fossil clues within isotopic abundances reveal. The scientific literature describing the highlights related here fills thousands of published technical papers. No attempt is made herein to provide attributions to them. For a scientist, finding the reference is the easy part; it is finding the idea that is hard. This book is intended to be not a source of references but of scientific ideas and related phenomena.

For anyone wanting to read more, monographs are more accessible than the research-journal literature. Insofar as understanding of the conceptual issues is concerned, almost all of those concepts can be drawn from six books, which contain ample references to the scientific journals.

Principles of Stellar Evolution and Nucleosynthesis, Donald D. Clayton (McGraw-Hill: New York, 1968; University of Chicago Press: Chicago, 1983)

The Evolution and Explosion of Massive Stars II. Explosive Hydrodynamics and Nucleosynthesis, Stanford E. Woosley and Thomas A. Weaver, *Astrophysical Journal Supplement*, **101**, 181 (1995)

Supernovae and Nucleosynthesis, W. D. Arnett (Princeton University Press: Princeton, 1996)

Nucleosynthesis and Chemical Evolution of Galaxies, B. E. J. Pagel (Cambridge University Press: Cambridge, 1997)

Astrophysical Implications of the Laboratory Study of Presolar Materials, T. Bernatowicz and E. Zinner, eds. (American Institute of Physics: New York, 1997)
Meteorites and the Early Solar System, J. F. Kerridge and M. S. Mathews, eds. (University of Arizona Press: Tucson, 1988)

I was fortunate to have become involved early in the questions of nucleosynthesis in stars, when tenacious questioning could expose key nuclear and astrophysical issues. Hoyle's sweeping canvas was inspiring, but significantly incomplete; and some processes were misleadingly formulated or not envisioned in the epochal 1957 exposition by Burbidge, Burbidge, Fowler and Hoyle (commonly cited as B^2FH). The opportunity fell to me with Caltech colleagues to formulate mathematical solutions for the s process and the r process of heavy-element nucleosynthesis, to discover the quasiequilibrium nature of silicon burning, to reformulate the e process for radioactive nickel rather than iron, and, with my Rice colleagues, to show how explosive oxygen and silicon burning can lead to an alternative quasiequilibrium known as "alpha-rich freezeout" if the peak temperature is high enough, and how a neutron-rich version of that alpha-rich quasiequilibrium accounted for many neutron-rich isotopes. Motivation to demonstrate the correctness of this post-B^2FH picture presented the chance to predict astronomical tests for gamma-ray-line astronomy and to predict presolar grains of outlandish isotopic compositions. I experienced the joy of asking these previously unasked questions, and to see their dramatic observational confirmations. These gave excitement to my scientific life and account for my eagerness to share a naturalist's stories, as they are found within the chart of the nuclides.

I have not tried to address all scientific areas in which isotopes play a role. To do so would vastly overreach my goal. Medical research lies beyond my qualifications; and those applications of isotope tracers are man-made rather than natural. I choose to emphasize the natural manifestations, those that occurred through nature's laws rather than through human technology. Even so I have omitted those natural small isotopic fractionations that living things display and that are generated by the natural laws of biochemical evolution. Except for a few culturally related remarks I have largely omitted geology. Isotopic tracers are of very great significance to human understanding of geologic science. My choice, however, is to omit those isotopic abundance signals that inform of the natural evolution of the Earth. Because I am interested in those isotopes that maintain natural abundances over long times, I am not addressing the huge numbers of radioactive isotopes that have so many applications by man. Only naturally occurring radioactivity is essential to the cosmic origin and evolution of matter. And even in the cosmic applications I omit many that the reader may wish to be aware of. In the case of cosmic rays I mention only a few specifics of their abundances, giving short change to most of the isotopic alterations that occur within their abundances as they collide with interstellar atoms. For interstellar molecules, as observed so brilliantly by radio astronomers, I give only inklings of the clues to interstellar chemistry that are provided, limiting my reporting to several dramatic instances of isotopic selectivity in interstellar chemistry. I have tried, in the interests of brevity and of focus, to concentrate on the origin and evolution of matter in the universe.

Finally, it is important to not misrepresent the true nature of science. Science is neither a collection of facts nor of their interpretations; and this book is largely a collection of facts and interpretations. Science itself is a mosaic of methods, hypotheses, ideas, criticism and above all, *skepticism*. Scientific knowledge is never really known to be true, unless it is so by human definition. The skeptical challenges to conventional wisdoms have always provided great scientific rewards. So in writing of the interpretations that mankind has placed on the peculiar circumstances surrounding each isotope, I write of them as if they were incontrovertible. I may hint at but do not document the uncertainties, the competing interpretations, the controversies that are the lifeblood of knowledge. These the reader can imagine for himself or herself.

Donald Clayton