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# Introduction

Nuclei are nature's primal species. Most came into being before life emerged on Earth. Each atomic nucleus has its own characteristics: its mass, its number of constituent elementary particles, its spin rate, its magnetic strength, its electric charge, its multitude of excited forms, each form with its own set of properties. Unlike life forms, where modest variations exist within a given species, all nuclei of a given type are identical – exactly the same as far as any measurement has ever revealed. The exactness of the replicas is remarkable, totally outside of common human experience. They are totally indistinguishable, one from another. They are perfect clones of a master form understood latterly by mankind in terms of the quantum physics of particles. A fundamental goal of physics, maybe one should say "a dream" of physics, is to understand each species in terms of a fundamental set of laws governing the indivisible particles of which each is assembled. Despite unprecedented progress in understanding, this goal still eludes mankind. It may ever elude us. Nonetheless, a formidable description of the physics of the atomic nucleus now exists. The community of nuclear physics gains each year more sophistication in its formulation of this realm of quantum mechanics. This realm extends from the elementary quarks, from which it seems that constituent nuclear particles – neutrons, protons, mesons – are constructed, to the fluidlike phenomena observed when one nucleus containing many protons and neutrons collides with another. This is the subject of textbooks, monographs, and popular books on nuclear and elementary particle physics; and it is not the goal of this book.

We experience these nuclei in their lowest energy states, called their "ground states," nuclei "unheated," without any extra energy of excitation, through to a myriad of distinct energized forms, or "excited states." We do not experience the atomic nuclei in daily life, however. But we can locate them and study them resting at the centers of atoms. The atoms are much larger than these central nuclei, about 100 000 times larger, owing to the orbits of electrons that revolve around each nucleus. It is the whole atom, specifically these orbiting electrons, that gives each nucleus its chemical properties. The entire science of chemistry concerns itself with how the electron orbits of one nucleus interact with the electron orbits of another. The orbiting electrons make of each nucleus an atom of a chemical element. Each atom is itself electrically neutral, because their several electrons each carry identical negative electric charge, that, taken together, in sum, exactly cancel the positive electric charge that resides in the nucleus at the atomic center, a positive charge that is one of the distinct properties of each nucleus. Every nucleus of a given chemical element carries exactly the same value for



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the positive charge on its nucleus. And the chemical properties of that element are determined by that charge.

This book concerns the relative numbers of the nuclei. It considers their properties and the numbers of each kind that are found to exist naturally, that is to say, that are found in natural settings. The attempt here is to describe the applications to mankind's knowledge of the world that can be discerned from the populations of the isotopes found to occur in nature. Many demonstrations concerning the history of the universe derive from the numbers of each species, which differ among astronomical objects.

When humans speak of a species, we normally think of living species, of tigers, of sea gulls, of oak trees, or of dandelions. The rich beauty of our experience reflects our appreciation of their various forms and numbers. The sea gull is far more numerous than the tiger. We speak normally of their population, rather than of their abundance; but it is the same idea. We are now accustomed to interpret the living populations not as the will of a Creator, but in terms of a dynamic ecological balance. Each species feeds off others. Each is devoured by predators. Each copes with the environment. The populations of species reflect aspects of their fitness for this struggle, and for their parallel struggle with the changing face of the Earth. So the populations represent not precisely fitness, for in some sense all are fit, but rather the numbers that can coexist within this ecological balance. Populations come into balance with their food supplies, and also with their risks. Mankind is a part of this balance, although we have difficulty in perceiving ourselves as part of a balanced fabric.

Nuclei too have populations. They come into being by being assembled from others. They are destroyed by transmutations into others. Their populations are determined by a balance within the universe that might poetically be described as ecological. Within that balance the total number of constituent nuclear particles is a fixed constant, or believed to be so in terms of the Big-Bang paradigm for the origin of matter and the evolution of the early universe. But the fixed number of nucleons (protons plus neutrons) does not fix the relative numbers of the diverse nuclear species into which the nucleons can be assembled. The populations of nuclear species record ancient events in the universe. The properties of each nucleus endow it with a different kind of "fitness" than that evinced by life; and that fitness plays a role in determining their present populations. Scientists commonly call the population numbers for nuclei their *abundances*. The distinct nuclear species vary hugely in their abundances, just as do the life species on Earth. Iron is millions of times more abundant than gold; just as are sea gulls in relation to tigers.

It is worthwhile to momentarily consider this subject in relation to the philosophical history of western ideas and culture. Long before atoms were known the Greeks developed philosophical ideas that remain part of our everyday thinking, even if not justifiable. Aristotle and Plato argued that although individuals within a species die and perish, the ideal form for their species is fixed and eternal. Differences among



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individuals could be seen as deviations from the ideal form. These ideas were strongly influenced by living forms. When Charles Darwin revisited this subject, he presented a revolutionary picture that replaced Aristotle's concept of a species as an eternal ideal form with concepts of groups of individuals making up competitive populations. To him the species became the abstraction and the groups of individuals the hard truths. Groups of individuals made up the populations whose numbers and characteristics reflected and determined their fitness. The *Origin of Species* described Darwin's idea of natural selection in analogy to the selections of plants and animals practiced intentionally by human breeding. Of this revolt Ernst Mayr has said, "No two ways of looking at nature could be more different." Lingering public belief after 2000 years of acceptance of the "ideal form" concept accounts for the public sense of horror at intentionally replacing a gene in one species by a gene from another species. Of this tension between the holistic ideal and the material reductionist way of thinking, Keith Davies has written: "This tension maintains openness and is progressive. For science to have a healthy future, the balance between these approaches must never become dogmatic. Our imagination gives our guesses a holistic basis, our reductive experiments a way to falsify them. The confrontation is essential."

Darwin's scientific reductionism won the day. And yet an irony occurs when we consider the populations of nuclei instead of the populations of living species. Each proton is identical, conforming in perfection to the Platonic and Aristotelian ideal. So too is each $^{12}C$ nucleus identical to all others. Plato and Aristotle surely would have embraced these examples of perfect replication of the eternal form, perhaps finding some ultimate good that allowed them their perfect adherence to the universal form. Today we have invented the principles of quantum mechanics to make good this Aristotelian victory. No genetic evolution accompanies the competition among populations of nuclei during evolution. But Darwinian ideas nonetheless find their place in the history of the isotopes. The natural environments of the interiors of stars find one nucleus more fit than another, and hence its ultimate population becomes greater. Some irony surely lies in finding that this history embraces aspects of both the Aristotelian and Darwinian pictures in that ancient philosophical debate.

The fascination with the abundances of the atomic nuclei is that they inform of ancient events. The events that are recorded in their populations depend upon the material sample in question. In the crust of the Earth, they record its geologic evolution. Silicon in that crust is much more abundant than iron, for example, because the Earth's crust is sandy, whereas its iron sank to the Earth's core during its early molten state. In the Earth's oceans the elemental abundances reflect their solubilities in water. In the Earth's atmosphere, their numbers reflect their volatilities. And so it goes. Such abundance-sets reflect and record the geophysical history of the Earth and the chemical properties of the chemical elements. Atmospheric carbon dioxide ($CO_2$) and methane ($CH_4$) record an extra wrinkle, the impact of human beings on the Earth's atmosphere.



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That the populations of nuclei depend on the sample being examined holds true throughout the universe. In differing samples the bulk abundances have differing physical significances. One may seek the total number of each specific kind of atom in the solar system, for example. Today these reside overwhelmingly within the Sun owing to its dominant mass, although complemented to lesser small degrees by the planets. One speaks of this set of abundances as "solar abundances." Determination of their values is itself a lengthy scientific quest, and it is not over. New NASA space missions greeting the millenium will continue this quest to know the solar abundances. Historically the solar abundances are regarded as those that existed 4.6 billion years ago in the interstellar cloud of gas and dust from which our solar system was soon to be born. Human experience has been limited to these abundances throughout our lengthy evolution, and only very recently has mankind sampled the stuff of other worlds and compared it to ours. That comparison pulses with scientific excitement.

At other times and other places in our universe the sets of elemental and isotopic abundances differ from the solar abundances. Astronomers first noticed this in other stars. The abundances of atoms in stars can be inferred from the strength of the atomic light that arrives at Earth from each star. Superimposed on their continuous distribution of light wavelengths, or colors, are the unmistakable atomic lines that identify the chemical elements in those stars as being the same chemical elements that exist on Earth. *Atomic lines* are light with exactly specified wavelengths, the fingerprints of the chemical element. Indeed, this sameness agrees with the interpretation of quantum mechanics and with the belief that the laws of physics should be the same throughout the universe. As far as one understands, the entire universe not only does contain but must contain only the same elements that we know here on Earth. Because physics is universal, so too are the elements universal. It is their populations that are not universal, but vary from sample to sample.

But the relative strengths of atomic lines differ from star to star. The confluence of atomic physics, of quantum mechanics, and of statistical mechanics has allowed astronomers to understand these variations in detail. These issues were at the heart of the revolution that was 20th-century physics; but today they are understood. The net result is that other stars have different abundances of the elements than does our own. Perhaps one should say "modestly different." The broad comparisons between the elements remain valid – iron is quite abundant, vanadium is rather rare. That remains true; but many stars have many fewer of each. A few have more of each. This was a great discovery of 20th-century astronomy, because it established the *nucleosynthesis* of the elements as an observational science. Astronomers also learned how old the stars are, for there do exist telltale signs of a star's age. The oldest stars are found to have many fewer of all chemical elements (except the three lightest elements) than does the Sun. These came to be called metal-poor stars, because the heavy elements were lumped together under the term "metals" by astronomers. It may seem paradoxical that the oldest stars have the fewest metals; but the key is that the abundances within



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each star record the abundance of metals in the gas from which the star formed. The most metal-poor stars in our Milky Way galaxy of stars have only 1/10 000th of the iron atoms (in comparison with hydrogen) as the Sun. These are also the oldest stars, probably among the first to be born in the infancy of the Milky Way.

During the period 1960–80 it became increasingly clear that the earliest stars to form in our Galaxy did so almost entirely from hydrogen (H) and helium (He), the two lightest elements (charge $Z = 1$ and $Z = 2$, also called "atomic number"). It became clear too that stars forming later had more of the heavier elements in relation to hydrogen and helium. Stars came to be characterized by their ratio of iron to hydrogen, written Fe/H by use of the chemical symbols for the elements iron and hydrogen; and this is called the *metallicity* of the star. The first stars inherited gas having the lowest metallicities, and those forming later, that is "younger" stars, inherited gas having increasingly higher metallicity. The metallicity of the Galaxy's gas has increased with time. This empirical base substantiated the theory of nucleosynthesis in stars, an idea that had arisen theoretically.

The theory of nucleosynthesis in stars was set forward by Englishman Fred Hoyle, first in 1946 and in improved detail in 1954. It had previously been thought possible that all of the chemical elements had been created at the beginning of the universe. Some attributed this to God. Theories of cosmic creation were invented that utilized a much more dense early epoch of the universe, one in which the heavy elements might possibly have been created by action of nuclear physics. This wave was fueled by Hubble's characterization of the expansion of the universe, observed by astronomers, and by the birth of cosmology based on Einstein's relativistic theory of gravity, which replaced Newton's theory. These rationalized the decisive fact of the expanding universe. They also required an early epoch that was increasingly more dense and hot as one looks backward to the beginning of time. This is called the "Big Bang." And the modern nuclear theory of the Big Bang showed that the ashes of that dense hot early universe would be the three lightest elements (H, $Z = 1$; He, $Z = 2$; and Li (lithium), $Z = 3$). Furthermore, the relative abundances of those elements agreed with the values found in stars. For the first time mankind understood that the universe *should have begun* with hydrogen and helium comprising more than 99% of all atoms, and in the ratio H/He = 10/1, just as observed in old stars. This was a very great triumph of human natural philosophy, combining parts of nuclear physics, the relativity theory of gravity, particle physics, and quantum statistical mechanics – all buttressed by observational astronomy.

In the 1950s and 1960s Hoyle's interpretation, that the heavier nuclei were synthesized from lighter nuclei within the interiors of stars, took hold. More detailed formulations of pieces of Hoyle's theory were set forth by others, especially A. G. W. Cameron and W. A. Fowler but also by this writer and others. These were buttressed by a great increase in the knowledge of the relative abundances of the chemical elements that was being provided at the same time by geochemists studying meteorites.



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Geochemists, especially V. M. Goldschmidt, Hans Suess, and H. C. Urey, argued in a 1956 review paper that the meteorites gave a good solar-system sample of the heavy elements that had not been fractionated by geochemistry. They were not only able to provide a reasonably accurate compilation of the abundances of the elements, but they also saw in rough outline how those heavier than iron might have been assembled by the capture of neutrons by lighter elements. These ideas were reinforced in 1957 by Burbidge, Burbidge, Fowler and Hoyle in a famous review paper (which came to be referred to by an acronym built from the authors's names, $B^2FH$). I joined this quest in 1957 and participated in improved quantitative formulations of the process involving slow capture of neutrons in stars (the s process) and of the process involving rapid capture of neutrons in stars (the r process). In the late 1960s Hoyle's e process for synthesizing $^{56}$Fe was replaced by quasiequilibrium synthesis of $^{56}$Ni instead. These years created a compelling picture of the origin of almost all of the nuclei within the interiors of the stars as they aged, contracted, heated, and finally exploded. But the problems were by no means solved, for new knowledge invariably increases ignorance as well, because previously unasked questions emerge. Not only does that process of discovery continue today with refinements of the stellar settings and of the nuclear reaction rates, but meteoritics and cosmochemistry have made equally great strides delineating the abundances of the elements and their isotopes.

Only the five lightest elements owe their abundances to origins outside the stars – the first three in the Big Bang and the fourth and fifth (beryllium and boron) by cosmic-ray interactions with interstellar atoms. From the stars came all the rest. From atomic number $Z = 6$ (carbon) to atomic number $Z = 94$ (plutonium), we look to the stars. This range of atomic numbers includes all of the common elements of human experience on Earth, save for the hydrogen within the water that blesses the Earth's surface. Textbooks provided standard learning vehicles for the stellar nucleosynthesis theory for generations of astrophysicists, who cemented the theory with hundreds of brilliant papers on an incredibly large number of observable manifestations of the theory and of astronomical tests of it. The poet Walt Whitman divined, in *Leaves of Grass*, this mystic hope:

> I believe that a leaf of grass is no less
> than the journeywork of the stars.

This theory was launched with renewed fervor by discovery in the 1970s of solid samples carrying isotopic ratios that differ from those on Earth. These solid samples came from the meteorites. Meteorites as a whole are rubble piles of stones made in the early solar system; but some of those stones "remembered" the unusual presolar isotopic compositions of the grains from which they had been assembled. Isolated somewhat later were pieces of stardust, refractory dust grains that had condensed during cooling of the gases ejected from specific single stars, and which recorded the isotopic compositions of each of those stars. These were first characterized in the



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laboratory in 1987 with the aid of isotopic predictions for them made a dozen years earlier. These solid fragments of stars could be studied in laboratories here on Earth! They were diamonds, silicon carbides, graphite, silicon nitride, aluminum oxide, and others. Suddenly mankind possessed measurements of stellar isotopic ratios that were accurate to 0.1%, far better than any astronomer of conventional type could hope for. These presolar grains could be sorted into stardust families, and their stellar parents identified. Instead of that one isotopic composition that we on Earth inherited from our birthing molecular cloud, we have thousands of accurate measurements of other isotopic compositions. The new challenge to nucleosynthesis theory was immediate and invigorating. During this same period radio astronomers began measuring the isotopic ratios of elements within interstellar molecules. These too gave a diverse and fascinating account of an interstellar gas that had not completely mixed, and that had evolved in time to new and changing isotopic structures. Our solar system could be clearly seen for the first time as but one point within space and time, that huge framework of astrophysics and cosmochemistry. This could be understood, if at all, only with the aid of the theory of synthesis of elements in stars.

To share nucleosynthesis theory is, however, also not the primary goal of this book. Books on the theory already exist. Rather it is to introduce and summarize fascinating and varied aspects of the abundances of the elements and their isotopes. Those abundances, and how they are interpreted within the theory of nucleosynthesis, are my real topics. Each isotope of each element has a far-reaching tale to tell. And if you do not share the technical interest of the scientist, you may share the impulse of the poet. In material both dry and technical from one point of view one uncovers a canvas of brushstrokes no less than that of Turner's Venetian sunbursts. Those brushstrokes too are dry and technical; and yet they give song to the human spirit. This book invites the reader on my journey of four decades, coming to know each isotope intimately. Each one of them, some 286 that exist naturally on the Earth and in the universe, has its own personality within cosmic evolution. For example, the personalities of the mass-181 isotope of tantalum, written $^{181}$Ta, and of the mass-56 isotope of iron, $^{56}$Fe, differ as dramatically as those of the sea gull and the tiger.

One can not progress far toward this goal without more specific consideration of the isotopes of the elements. The distinct isotopes of a given chemical element differ in their masses and associated properties of their nuclei. Each isotope of a given chemical element has the same nuclear charge, has therefore the same number of orbiting electrons in its structure, and has therefore the same chemical properties. Each isotope of oxygen behaves chemically as oxygen. The distinct isotopes of oxygen have distinct nuclear masses because their nuclei contain differing numbers of neutrons, the uncharged nucleon. By contrast, the number of positively charged protons determines the nuclear charge and the chemical identity of the element. The extra neutrons just go along for the ride insofar as chemistry is concerned. One speaks of each nucleus by the numbers of these constituent nucleons: $Z$ for the number of protons, the



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so-called "atomic number"; $N$ for the number of neutrons; and $A$ for their total. That is, $A = Z + N$, where $A$ is the "mass number" (nucleon number). To again use the example of oxygen, each isotope thereof has the same number of protons, $Z = 8$. But there exist three stable isotopes, $A = 16$, $A = 17$, and $A = 18$. From the sum of nucleons it is evident that these contain respectively $N = 8$, $N = 9$, and $N = 10$ neutrons within their nuclei, so that they produce the three mass numbers for oxygen. As a matter of notation these are conventionally written with the mass number as a preceding superscript: $^{16}O$, $^{17}O$ and $^{18}O$.

Cosmic portraits of the isotopes are the main burden of this book. For each element there is an historical and chemical introduction, followed by a table of those isotopes of that element that have observed abundance in the natural world. Then a section on each isotope describes its nuclear characteristics, its abundance in the solar system relative to that of silicon, the means of nucleosynthesis of that isotope, astronomical observations of it, and its participation in isotopic patterns differing from those known on Earth, primarily in presolar grains extracted from the meteorites.



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# ELEMENTS

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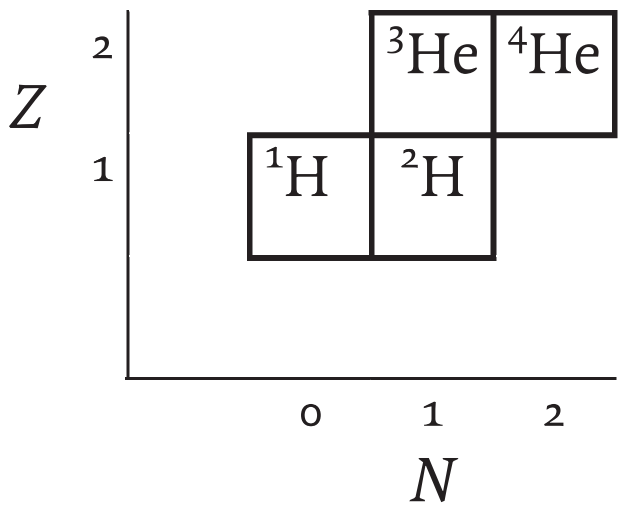


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