Inorganic Chemistry

A Guide to Advanced Study

by R. B. HESLOP
and P. L. ROBINSON

Second, Revised Edition

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Preface

This book is addressed to students and intended to provide in a single small volume an outline of current inorganic chemistry sufficient for basic reading up to honours degree standard. The approach is general and reasonably fundamental, so that some of the material is suitable for advanced level and scholarship pupils in schools and for non-specialist students in universities and technical colleges. Suggestions are made for further reading. Teachers may find it useful in planning their instruction to classes at all stages. An endeavour has been made to select factual matter of topical interest and to present the theoretical foundations rigorously enough to make advance possible by addition rather than correction.

Inorganic chemistry is descriptive in the sense that many branches of chemistry remain essentially descriptive. But the emphasis falls increasingly upon a description of its phenomena in terms of the discoveries of atomic physics, quantum mechanics, and theoretical and physical chemistry. Accordingly the earlier chapters seek to provide a minimum background for the rational understanding of chemical observations. The information is not intended to take the place of specific reading and instruction in physical and theoretical chemistry, but simply to give a handy, coherent synopsis of ideas which should enrich the appreciation of the chapters which follow.

These constitute the main body of the work which has three objects. First to provide clear-cut, readily assimilated information about the elements, presented in a comparative way, usually, but not exclusively, under the appropriate periodic sub-groups; secondly to cross-link related material by short discussions of particular topics; and thirdly to emphasise, by reiteration and repeated page reference, applications of theory developed in the earlier chapters. By these modes of association, it is hoped the student will both acquire a useful body of information and appreciate the growing integration which now characterises inorganic chemistry. Although short, and intended as a framework for planning his study, this book includes something on most aspects of the subject. Its character makes direct reference to original literature out of place; but, in some instances, authors' names and the year of publication have been given.

The varied and interesting experimentation pursued in modern inorganic chemistry has been outlined elsewhere; the brief reference that has been possible here will, it is hoped, suggest that inorganic chemistry is an actively experimental subject.

As is inevitable in a new text-book on an old subject, we have, besides drawing on our own experience, consulted many original papers, articles and books; without the efforts of their authors we could not have written

these pages. To Dr. T. G. Pearson and Dr. B. A. Scott we are very grateful, for they undertook the considerable and unenviable task of reading the first draft, and their stimulating criticisms and valuable suggestions were most acceptable. We are especially indebted to Dr. R. McWeeny who actively collaborated in the writing of chapters 4, 5, 6 and 8, and largely brought them to their final form. He also read and criticised the remaining chapters, and his influence on the presentation of theoretical topics throughout the book is very cordially acknowledged. For the text in its final form we accept responsibility.

We thank Mr. J. Routledge who prepared the diagrams, all specially drawn for this work, and Mrs. A. Bartrope who typed the manuscript and gave much other help.

January 1960   R. B. HESLOP
                                                                    P. L. ROBINSON

Preface to the Second Edition

Four further impressions of this book have been called for since it was published in April 1960. This fact and much encouraging comment suggest that the selection of material and the manner of its presentation have met with general approval. We are grateful for many helpful criticisms—made personally and in reviews—all of which have been carefully considered. Wherever possible, modifications to meet them have been made in this second edition.

The original aim, which remains unchanged, was a text-book of modest size and price that did not presume to be a substitute for oral instruction or seek to deal with the special topics which give individuality to advanced courses. Extending its scope to include even a selection of these topics would have destroyed the character of the book; hence the only major additions are a description of phosphonitrilic compounds, a section on complexes in aqueous solution, and a short chapter on inorganic polymers. In other parts the treatment has been modified to bring it into line with the results of recent research.

We have suggested useful sources of information on p. 3 and still feel that the further direction of reading should rest with the teacher.

We thank Dr. T. N. Bell, Professor N. N. Greenwood, Dr. M. F. Lappert, Dr. L. E. J. Roberts, Dr. A. G. Sharpe, Professor E. H. Wiebenga and Dr. W. Wild for the helpful suggestions they were kind enough to make.

September 1962   R. B. H.
                                                                    P. L. R.

Contents

An Approach to Inorganic Chemistry

A resurgence in inorganic chemistry, the oldest discipline in chemistry, is evident; not only is the subject exciting more interest as a topic of pure and applied research, it is finding manifold applications in industry. Inorganic chemistry forms the foundation of vast endeavour in fine and heavy chemicals, in ceramics, and in extraction metallurgy. The last, once restricted to a few, is now extended to most metals. It is concerned with the preparation of catalysts, and its ramifications in the field of atomic energy are extensive and growing. This book will have failed of its purpose if something of the enthusiasm and confidence now inspiring inorganic chemists has not been reflected in its pages. Distinguished exponents of the subject have recently called attention to much that awaits investigation. Apart from research, the calls of industry for inorganic chemists, at present inadequately met, grow.

In this opening chapter we shall try to show what constitutes inorganic chemistry, why we think it desirable to adopt a modification of the usual approach to the subject, how we believe this book can best be used and, finally, what symbols and contractions we have used to get all we wished within these 576 pages.

Inorganic chemistry

The ambit of inorganic chemistry is well established; it comprises the natural occurrence and artificial preparation of the elements, their properties and reactions, and those of their compounds, together with a rational correlation and theoretical interpretation of the phenomena. Most of the compounds of carbon lie outside this purview, though interest in organic ligands widens.

Having been the first of the major divisions of classical chemistry to be treated didactically and, consequently, earliest a subject for text-books, inorganic chemistry has suffered the pioneer's penalty in its exposition. The historical approach, so natural and rewarding at the beginning, has been too long retained. Because facts are more readily recognised than their significance, accumulation has tended to outrun selection. Systematisation of the accumulated material became possible much later, relatively, than in either organic or physical chemistry. As a result inorganic chemistry has tended to

be presented as a mass of arbitrarily chosen facts which have been brought into some relationship by the Periodic Table.

Modern inorganic chemistry remains essentially descriptive and pictorial, though the pictures increase in precision and the descriptions become less and less qualitative. The historical approach, formerly much favoured, is now inappropriate because a point has been reached in the development of the subject from which it is easier and less confusing to enter it at the level of present theoretical and physico-chemical knowledge. This book attempts to provide such an entry.

Departure from custom

It is customary in text-books of inorganic chemistry to discuss, sometimes at length, two topics which belong more properly to general and historical chemistry, namely the earlier work on the structure of the atom culminating in the atomic model of Bohr, and the development of the idea of periodicity in the properties of the elements with details of its tabular presentation. Both have been omitted from this book because they hamper a rapid, lively development of the subject which stimulates interest in the student.

Approach to the subject

Quantum theory has provided a picture of the atom that allows an immediate approach to valency and molecular structure while furnishing a far more secure basis for the periodic arrangement of the elements than selected physical and chemical properties. This is not to denigrate the achievements of Thomson, Rutherford and Bohr in atomic structure, or of Newlands, Lothar Meyer, Mendeleeff, Bohr and others in evolving the Periodic Law, but rather to seize upon developments which their prescient work made possible. Readers will find it easier to assimilate and remember the facts embodied in the Periodic Classification when these are seen to emerge from the systematic development of electronic structure with increasing atomic number.

The description of atoms and molecules which has been adopted—that of one or more positive nuclei surrounded by a cloud of electrons which, for many purposes, is equivalent to a smeared-out negative charge—presents in pictorial form the results of thirty years of quantum mechanics. All available evidence suggests that this general picture is unlikely to suffer substantial modification. Theoretical chemistry accepts the Schrödinger equation and is largely concerned with finding the most direct mathematical path to a unified and transparent explanation of the physico-chemical prop-

erties of molecules. The adoption of this kind of description is therefore believed to be both desirable and opportune. The nucleus itself forms a useful starting point in this approach, not only because its charge and mass determine the extranuclear structure of the atom, but because it is the seat of radioactivity and the source of nuclear energy.

The reason why chemical reactions take place and the mechanism by which they operate are matters of increasing interest and call for some knowledge of thermodynamics and kinetics. The brief excursions into these subjects are synoptic and intended to provide the reader with no more than he will need in pursuing the main part of the book. Information about the kinetics of inorganic reactions is still sparse, but there is a wealth of thermodynamical data, standard electrode potentials and dissociation constants and the student must acquire facility in using these figures.

So much of inorganic matter is crystalline that once a means of investigating the structure of solids became available it was eagerly applied. The result has made it necessary to include a short account of the solid state. With this goes a little about the growth of crystals and the way atoms in their lattices suffer dislocation.

Suggestions

This book is a brief epitome of modern inorganic chemistry and the reader may usefully begin where his interest lies. Liberal cross-references provide a constant link with definitions and underlying theory. The earlier chapters need not be mastered before the rest of the book can be understood, but their assimilation by repeated reference will be repaid by a fuller appreciation of what follows. It is idle to suppose that a real appreciation of any branch of chemistry can be had without two things—adequate theory and sufficient facts. The best way to grasp theory is to apply it constantly, and the easiest way to remember facts is to seek their theoretical relationship. To continue from the stage reached in this book the student has a great choice of reading.

There are the larger standard texts, the books including many topics or dealing with one, a number of articles in *Quarterly Reviews of the Chemical Society*, some monographs of the *Royal Institute of Chemistry* and many other excellent presentations of current inorganic topics in *Chemistry and Industry*, the *School Science Review* and the *Journal of Chemical Education*. Other standard sources of reference and some account of laboratory methods will be found in *Experimental Inorganic Chemistry* by R. E. Dodd and P. L. Robinson.

Symbols and Abbreviations

1. Chemical symbols and formulae have been frequently used in place of names to save space and often to secure clarity. Where an arrow ($\rightarrow$) from the donor atom appears, it does not imply that the bond is different from the rest.
2. Where there can be no confusion as to the temperature scale, °C is indicated by the degree sign only after a number.
3. For pressure, mm signifies mm of mercury.
4. The numerical values of properties are intended for comparative purposes; they are given to no greater accuracy than this requires.
5. Atomic radius, density and atomic volume data are for the form stable at 25° and 1 atmosphere, except where otherwise stated.
6. Symbols which appear frequently are:

Avogadro's number	N	Heat capacity	C (cal mole^{-1} deg^{-1})
Gas constant	R (cal mole^{-1})	Internal energy	U (cal)
Faraday's constant	F (coulombs)	Entropy	S (cal deg^{-1})
		Heat content	H (cal)
Charge on an electron	$-e$ (coulombs)	Gibbs free energy	G (cal)
		Atomic number	Z
Planck's constant	h (erg sec)	Atomic mass number	A
		Concentration of X	$[X]$ moles l.$^{-1}$
Frequency	ν (sec^{-1})	Activity of X	a_x or $\{X\}$
Wave number	λ^{-1} (cm^{-1})	Specific reaction rate	k
Wave length	λ (Ångstrom units)	Equilibrium constant	K
		Activation energy	E (cal)

Subscripts and superscripts when used with these symbols, are explained in the text. The units of k and K are variable.

7. The most frequently used abbreviations are:

g	gram	mole	gram molecule
kg	kilogram	h.c.p.	hexagonal close-packed
l.	litre	b.c.c.	body-centred cubic
ml	millilitre	f.c.c.	face-centred cubic
cc	cubic centimetre	At. Vol.	atomic volume
cm	centimetre	A.M.U.	atomic mass unit
Å	Ångstrom unit (10^{-8} cm.)	b.p.	boiling point
V	volt	m.p.	melting point
eV	electron volt	u.v.	ultraviolet
MeV	million electron volts	i.r.	infrared
$I(1)$	ionisation potential (first)	atm.	atmosphere (pressure)
$E_A^o(M^+/M)$	standard electrode potential for M$^+$/M couple in volts	dens.	density
		s.g.	specific gravity
e.m.f.	electromotive force (volts)	°K	degree Kelvin
cal	calorie	Gp. II. etc.	Periodic Group Two etc.
kcal	kilocalorie	ln x	logarithm of x to base e

The Atomic Nucleus: Genesis of the Elements

The chemical properties of an element depend on the nature of its atoms, and many advances in chemistry are directly attributable to advances in atomic physics during the last half century.

An atom comprises a positively charged, central *nucleus* which occupies about 10^{-15} of its volume, has a radius of $\sim 10^{-13}$ cm, and accounts for nearly all its mass, surrounded by a region of negative charge produced by the *electrons*, the whole unit being electrically neutral. The nucleus contains positive *protons* and uncharged *neutrons*, both particles having about the same mass. Other particles are known to emerge from the nucleus (*e.g.* electrons, p. 17, and positrons, p. 18) but are not regarded as primary constituents and are only observable in a transient sense. This apparent paradox is a manifestation of the Uncertainty Principle (p. 44): if the position of an electron is known within extremely narrow limits (as in a nucleus) its momentum can be known only within extremely wide limits; this means an electron known to be within a nucleus at one instant has a high probability of escaping during the next instant, *i.e.* it cannot be regarded as a permanent constit-

TABLE 1

CONSTITUTION OF SOME NUCLEI

Element	Z	N	A	Symbols		Properties
Hydrogen	1	0	1	$^1_1$H	p	Stable
Deuterium	1	1	2	$^2_1$H	d	Stable
Tritium	1	2	3	$^3_1$H	t	Radioactive
Helium	2	1	3	$^3_2$He		Stable
	2	2	4	$^4_2$He	α	Stable
Lithium	3	3	6	$^6_3$Li		Stable
	3	4	7	$^7_3$Li		Stable
Sodium	11	11	22	$^{22}_{11}$Na		Radioactive
	11	12	23	$^{23}_{11}$Na		Stable
	11	13	24	$^{24}_{11}$Na		Radioactive

uent. The number of protons in the nucleus determines the nature of an element; it equals the number of electrons which in turn fixes the chemical character. An atom with eight protons is oxygen, one with seventeen protons chlorine. This, the *atomic number* Z, fixes the place of the element in the Periodic Table. Except for hydrogen, all nuclei also contain a number of neutrons, N. The sum of Z and N is the *mass number*, A. Protons and neutrons being known collectively as *nucleons*, A is the number of nucleons.

An atom has three noteworthy features: (*i*) the enormous density of the nucleus, about 5×10^{12} times as dense as uranium; (*ii*) the small volume of the nucleus, about 10^{-15} of that of the atom, (*iii*) the large volume of the negatively charged cloud, about 10^{15} times that of the nucleus. Nevertheless atoms have diameters which do not differ greatly, the largest being only five times greater than the smallest.

TABLE 2

APPROXIMATE DATA FOR NUCLEUS, ELECTRON CLOUD AND ATOM

	Nucleus	*Electron Cloud*	*Atom*
Charge (coulombs)	$+1.6 \times 10^{-19} Z$	$-1.6 \times 10^{-19} Z$	—
Mass	A	$Z/1837$	A
Diameter (cm)	$1.5 \times 10^{-13} A^{\frac{1}{3}}$	10^{-8}	10^{-8}
Density (g/cc)	10^{14}	$2 \times 10^{-4} Z$	$0.4 A$
Charge density (coulombs/cm³)	5×10^{18}	$4 \times 10^4 Z$	—

Isotopes

There are three types of hydrogen atoms and, unlike any other isotopes, they have names: *protium, deuterium, tritium*. In the commonest, protium, the nucleus is a proton. Terrestrial hydrogen is usually combined with other elements, and one atom of hydrogen in six thousand has a nucleus containing a neutron as well as a proton. This isotope, deuterium, was separated from ordinary hydrogen in 1931 (Urey, Brickwedde and Murphy) and has somewhat different properties from the latter. The third isotope, tritium, is produced by bombarding lithium ($^6_3$Li) with slow neutrons. Tritium is unstable, its atom reverting to helium of the same mass by loss of a *β-particle* (p. 17), an electron, in this instance, of nuclear origin:

$$^3_1\text{H} \longrightarrow {}^3_2\text{He} + \beta.$$

In a process of this kind the neutron decays into a proton and an electron. The respective hydrogen isotopes are designated $^1_1$H, $^2_1$H and $^3_1$H the superscript being the mass number, A, and the subscript the atomic number, Z.

These isotopes occupy the same place as hydrogen in the Periodic Table. Helium has two natural isotopes $^3_2$He and $^4_2$He, the former very rare, and lithium also two, $^6_3$Li and $^7_3$Li, occurring in the ratio of about 1:13. Though the mass number precedes the symbol, the isotopes are spoken of as lithium-*six* and lithium-*seven*. There is only one natural isotope of sodium, $^{23}_{11}$Na; the other two, $^{22}_{11}$Na and $^{24}_{11}$Na, are artificial and unstable, the lighter emitting positrons (p. 18) and the heavier electrons.

Besides *isotope*, there are two other useful terms: atoms with the same mass number and different atomic numbers are called *isobars;* those with the same number of neutrons, *isotones*.

TABLE 3

ISOTOPE, ISOBAR AND ISOTONE

	Z	A	N	Examples	
Isotope	Same	Different	Different	$^{31}_{15}$P	$^{32}_{15}$P
Isobar	Different	Same	Different	$^3_1$H	$^3_2$He
Isotone	Different	Different	Same	$^2_1$H	$^3_2$He

Though it is proper to refer to phosphorus-31 and phosphorus-32 as isotopes of phosphorus, an individual atomic species should be called a *nuclide*. The hundred or so elements have furnished about twelve hundred nuclides.

Isotopes were first recognised in the natural radioactive series which comprise heavy elements, but positive ray analysis (Thomson, 1912) showed that light elements also had isotopes and the development of the mass spectrograph (Aston, 1927) enabled all the elements to be investigated. The operation of the mass spectrograph is based on the deflection of collimated beams of positively charged particles, cations, in electric and magnetic fields of known strength. The ions are formed as an anode ray by evaporation from a hot filament or, as in Aston's earliest apparatus, by passing a discharge through a vapour. Adjustment of the strength of the fields enables particles of the same charge to mass ratio to be focussed as slit images. With such a beam from an element possessing isotopes, the several images are brought to different foci, and from their positions the masses of the individual isotopes may be determined with an accuracy of 0.01% or better.

Molecules have rotational and vibrational energies (p. 119) which are quantised, taking only certain discrete values which depend in magnitude on the masses of the atoms involved and are therefore different for molecules containing different isotopes of the same element, for instance ^{1}H^{35}Cl and ^{1}H^{37}Cl. Changes in rotational energy are characterised by the absorption of radiation in the far infrared, and in vibrational energy by absorption in

the near infrared; they give rise to lines in these spectral regions. Particular lines which occur singly when one nuclide is present appear in groups when there are several nuclides. From the small differences in frequency both the presence and relative masses of the nuclides may be inferred. By this sensitive method Giauque and Johnson (1929) showed that oxygen contained molecules of $^{16}O^{17}O$ and $^{16}O^{18}O$. The existence of oxygen-17 and 18 had not been revealed by the mass spectrograph.

Natural isotopic ratios — Atomic mass standard

The mass spectrometer is a mass spectrograph in which the ions are produced at a steady rate and the photographic plate, by means of which the positions of the ion images were formerly observed, is replaced by a slit behind which is a collector connected to devices for amplifying and measuring the ion current. The slit scans the spectrum and the ion current shows as a series of peaks. Every peak indicates an isotope and its height represents the relative number of ions (Fig. 1). The design of these instruments now
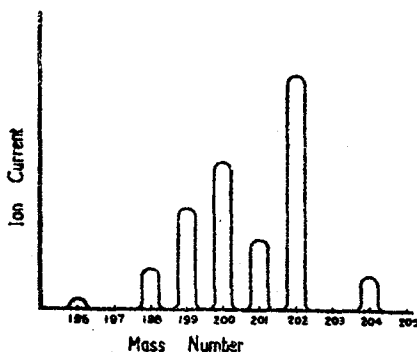

Fig. 1. Ion current peaks in the mass spectrograph of mercury.

allows an accuracy of 0.001%, making the method better than that of chemical analysis for the determination of atomic mass—the weighted mean of the masses of the isotopes.

The relative abundance of isotopes from different sources may vary a little. Atmospheric oxygen is slightly richer in oxygen-18 than the combined oxygen in sea water, and the relative abundance in water from different sources is not constant. Elementary sulphur in the Texas deposits has a different isotopic composition from that of the combined sulphur in the surrounding rocks. A range of 3.8% has been observed in the ratio of boron-10 and 11 from various sources (Briscoe and Robinson, 1925), but no

difference in the ratio of silicon-28, 29 and 30 in material of widely spaced terrestrial origin (Robinson and Smith, 1926).

Atomic masses have been expressed with the naturally occurring mixture of oxygen isotopes as a standard value of 16 (the chemical scale); a later scale was that based on the mass of the nuclide $^{16}_{8}O$ (the physical scale). Because of the two heavier isotopes present in ordinary oxygen, atomic masses on the physical scale are 1.000275 times greater than those on the chemical scale.

It is now recommended by the International Union of Pure and Applied Chemistry that the nuclide $^{12}_{6}C$ should be used as the basis of a unified scale. To bring them to the carbon-12 scale, atomic masses on the chemical scale must be reduced by 43 parts per million (multiplied by 0.999957). No atomic mass is changed by more than 4 in the last place quoted in the 1957 table, and few of these have been established with certainty to better than 5 in the last place. The carbon-12 scale is very suitable for expressing the masses of nuclides and has the advantage that very few of the present figures are affected by as much as their limits of error.

The Mole

In keeping with this rationalisation of the atomic mass standard, Guggenheim (1961) has proposed a definition of the mole which includes not only molecular species but atoms, radicals, ions and electrons. *"The Mole* is the amount of substance containing the same number of molecules (or atoms, or radicals, or ions, or electrons as the case may be) as there are atoms in 12 g of ^{12}C*"*. Mole has been used in this sense throughout this book.

Separation of isotopes

(i) *Gaseous diffusion*

Gases of different density, ϱ, diffuse at different rates: rate $\propto 1/\sqrt{\varrho}$. Uranium hexafluoride made from natural uranium contains one part of $^{235}UF_6$ in 140 parts of $^{238}UF_6$. The ratio of the densities is 1.0086, of diffusion rates 1.0043. A process of successive diffusion through a series of porous partitions was developed at Oak Ridge, Tennessee (1945), and has been modified elsewhere. In these the lighter fraction passes a barrier and becomes the feed for a later stage while the heavier fraction is returned to an earlier stage.

(ii) *Thermal diffusion*

When two gases of different densities are in a vertical tube which is cool and has an electrically heated wire down the axis, the lighter gas diffuses

preferentially towards the hot wire where it rises in a convection current, while the heavier streams downwards on the surface of the tube. The principle is applicable to isotopes and, with a column of 100 feet and a temperature difference of 600°, Clusius and Dickel (1938) effected an almost complete separation of ^{35}Cl from ^{37}Cl.

(iii) *Electromagnetic method*

A perfect separation is possible with a mass spectrograph in which the positive ions of the different isotopes pass into collectors, but the quantities would be small. About 1943, however, a large-scale apparatus, the calutron, was constructed in which an ideal rigorous separation was sacrificed to yield, since the ions in beams of heavy current repel one another and cause spreading. The method has been further refined and is extensively used.

(iv) *Molecular distillation*

Brönsted and Hevesy (1921) partially separated the isotopes of mercury by distillation in a high vacuum with a distance between the evaporating and condensing surfaces equal to about the mean free path of the atoms. The rates at which the isotopes evaporate is inversely proportional to the square roots of their masses so that the condensate is a little richer in the lighter isotopes.

(v) *Chemical methods*

Isotopes are not expected to be absolutely identical in chemical properties (p. 247), but the difference is observable only in the light elements where the ratio of the mass of the isotopes is large, for instance ^1H and ^2H. Thode and Urey (1939) concentrated nitrogen-15 in ammonium nitrate, to the extent of 70%, by allowing a solution of the salt to flow down a column against a counter current of ammonia. The equilibrium constant (p. 178) for

$$^{15}NH_3(g) + {}^{14}NH_4{}^+ (aq) \rightleftharpoons {}^{14}NH_3(g) + {}^{15}NH_4{}^+ (aq)$$
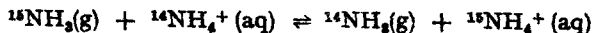
has a value of about 1.033.

(vi) *Gas chromatography*

This technique enables gases to be separated by the selective adsorption of one or more from a mixture on a suitable packing in a column. The adsorbed gas, should that be required, may be subsequently recovered by elution or other means. Though only partially successful when applied to the isotopes of neon because the difference in their adsorption coefficient on charcoal is small, the method has enabled deuterium to be separated from a 1 : 1 deuterium-hydrogen mixture (Glueckauf and Kitt, 1956). The

column is packed with palladium-black on asbestos which preferentially adsorbs the hydrogen and allows the deuterium to pass on.

Exact masses of nuclides

Precise determinations of the masses of nuclides have shown that they are not simply the sums of the individual masses of their component protons and neutrons. When these units or nucleons combine to form a nucleus there is a change of potential and kinetic energy which appears as a change in mass. Einstein showed the energy created by the destruction of mass and the mass destroyed to be related thus:

$$E = mc^2.$$

The velocity of light c is $\sim 3 \times 10^{10}$ cm.sec^{-1} and a mass of 1 g is thus equivalent to about 9×10^{20} ergs.

A unit of energy, the *electron-volt*, is used in discussing energy changes in nuclei. It is the kinetic energy acquired by an electron in falling through a potential difference of 1 V.

$$1 \, eV = 1.60 \times 10^{-12} \, ergs,$$
$$1 \text{ million eV, } 1 \, MeV = 1.60 \times 10^{-6} \, ergs,$$
$$\therefore \text{ a mass of 1 g} = 5.61 \times 10^{26} \, MeV.$$

An obvious result of Einstein's deduction is that the separate principles of conservation of mass and conservation of energy are replaced by the single principle of conservation of mass-energy. Furthermore, both mass and energy may be expressed in electron-volts, ergs or grams.

A convenient unit for the measurement of the masses of nuclides is the *atomic mass unit*, AMU, which is defined as one twelfth of the mass of the ^{12}C nuclide. The AMU $= 1.6604 \times 10^{-24}$ g; this is the reciprocal of the Avogadro number, 6.0228×10^{23} molecules per mole. It is equivalent to 931 MeV. The atomic mass or exact mass, M, of a nuclide is the weight of its atom, which includes the extra-nuclear electrons, in AMU. M is very slightly different from the mass number, A, in every instance except the standard, carbon-12. With sulphur-32, for instance, $M = 31.982183$ AMU, the difference $A - M$ (0.017817 AMU) being the mass defect. The *mass defect* formerly used as a guide to the stability of a nucleus has been replaced for this purpose by the more precise concept of *binding energy*.

Binding energy

When nucleons coalesce into a nucleus there is a loss of energy, shown as an equivalent decrease in mass; the binding energy, BE, is given by