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INTERMEDIATE STATE
TO NEUTRON RESONANCE LEVEL

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GENERAL, NUCLEAR, SOLID STATE, MOLECULAR
CHEMICAL, METAL AND VACUUM PHYSICS
ASTRONOMY, GEOPHYSICS, BIOPHYSICS
AND RELATED SUBJECTS

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INTERMEDIATE STATE (NUCLEAR THEORY). If it is energetically possible for a system to jump from an initial state (i) to the final state (f) then it can do so in two ways. In an allowed transition the system passes from (i) to (f) directly while in forbidden transition this is not possible and the transition takes place through one or more intermediate states, to which the transition is not forbidden and which lie energetically between (i) and (f). Energy need not be conserved in transitions to and from intermediate states. The reason for this is that the lifetime of such an intermediate state is so short that according to the uncertainty principle the energy change may be very large.

See also: Uncertainty principle.

INTERMETALLIC COMPOUNDS. An intermetallic compound is a compound of two or more metallic elements possessing a characteristic crystal structure and a specific composition or composition range intermediate to the primary solid solutions in the parent metals. I.C.'s are normally hard and brittle, have characteristic melting points (unless decomposing or transforming within the solid) and electrical conductivities and can sometimes be ferro- or strongly paramagnetic, where the components may not be. They can form from solid solutions either isocompositionally (e.g. sigma-phase in Fe-Cr) or by diffusion, and their practical interest lies more often in these nucleation and precipitation effects in alloy matrices than in their separate existence. Melting point and heat of formation are useful measures of stability of I.C.'s. Increased compound stability is associated with more restricted primary solubility.

The principal classes are: (1) Valency compounds, which tend to adopt atomic proportions in accordance with normal chemical valency rules. (2) Electron compounds, the structure and composition of which are determined by a definite number of free electrons per atom or more strictly, electrons per unit cell, allowing for defect lattices. The division between (1) and (2) is not rigid, there being many borderline and contentious cases which show characteristics of both. The main factors governing compound formation are atomic size factor, electrochemical valency and electron: atom ratio; each can predominate in varying systems and characterize the compound type formed. Predominance of one factor generally produces the simpler structures, of two or more the more complex ones.

Typical *valency compounds* are those of many metals with elements of the IVB, VB, VIB subgroups, such as:

	Type structure	Examples
AB ₂	CaF ₂ or related (cubic)	Mg ₂ Si, Mg ₂ Sn, Mg ₂ Pb, Cu ₂ Se, PtSn ₂ , CuMgBi
A ₂ B ₃	La ₂ O ₃ or related	Mg ₂ Sb ₃ , Mg ₂ Bi ₃ , Mg ₂ As ₃
AB	NaCl, Zinc blende and Wurtzite (cubic)	MgSe, MgTe, CaSe, PbTe, MgSb, MgTe
AB	NiAs (Hexagonal)	FeSe, CoTe, PtTe, NiSb, MnBi.

The NiAs type compounds form an extensive isomorphous family of Group: (IV, V, VI, VII, VIII) \leftrightarrow (IIIB, IVB, VB, VIB) metals; they are not necessarily restricted to ratios AB, but homogeneity ranges and stoichiometric changes occur (e.g. Ni₂Ge, Ni₂Sn₃); such ranges are facilitated by A/B atom substitution, as well as by the presence of lattice vacancies. This versatility is linked with easy axial ratio changes in the hexagonal lattice and with shear movements, a principle also applying to other compound groups, as does that of defect-lattice formation. Phenomena known in solid solutions, such as stacking faults and order-disorder transitions are also known in I.C.'s. Superlattices in primary solutions are often preparatory stages to I.C. formation on varying temperature or composition.

Electron compounds are exemplified by the following:-

Structure and E/A Ratio	Examples
Body-centred cubic 3:2	Cu ₃ Al, Cu ₃ Ga, CuZn, Cu ₃ Si, AgMg, AgCd, Ag ₃ Al, AuZn, FeAl, NiAl.
β -Mn type 3:2	Cu ₃ Si, Ag ₃ Al, CoZn ₂
Hex. c.p. 3:2	Cu ₃ Ga, Cu ₃ Ge, AgZn, Ag ₃ Al, Ag ₃ Sn
γ -brass type 21:13	Cu ₅ Zn ₈ , Cu ₅ Al ₄ , Cu ₃₁ Sn ₈ , Ag ₅ Zn ₈ , Ag ₅ In ₄ , Au ₅ In ₄ , Fe ₅ Zn ₈ , Pt ₅ Zn ₈ , Na ₃₁ Pb ₈ .
Hex. c.p. 7:4	CuZn ₃ , Cu ₃ Sn, AgZn ₃ , Ag ₃ Al, AuCd ₃

Electron compounds occur in numerous other systems, and subsidiary order-disorder effects are again known. In calculating the electron: atom ratio, zero valency has to be assumed for certain atoms, e.g. for (Fe, Co, Ni) in the γ -brass structure (Ekman), a fundamentally important discovery which evolved into the finding that a metal can vary its effective valency, including negative values, within a binary or ternary system, depending on composition and compound association. A characteristic of electron compounds is the existence of considerable homogeneity ranges for the component metals; favourable size factor is still a condition, limited to about 20% difference.

The *Laves phases* represent a further highly stable compound group: Composition AB_2 , size-factor slightly larger than for electron-compounds (characteristic radius ratio $r_A : r_B = 1.225:1$). Three sub-classes, typified by $MgCu_2$, $MgZn_2$ and $MgNi_2$, represent hexagonal and cubic variants to the same structural theme. Numerous A-B pairs (from diverse portions of the periodic table) can assume the Laves structures; some examples: $TiCo_2$, $AgBe_2$, UFe_2 , UAl_2 , ZrW_2 , $ZrFe_2$, $PbAu_2$, KBi_2 , $LaAl_2$, $NbFe_2$, $VaMg_2$, $MoBe_2$, ZrV_2 .

Some further I.C. classes, to which reference must suffice, are:

- (1) The sigma phases amongst transition metal (e.g. $FeCr$, $NbRe$, many others) of particular interest in industrial alloys and for isomorphy with β -uranium.
- (2) The aluminium-rich transition metal compounds (e.g. $FeAl_3$, $MnAl_3$, Co_3Al_2) mainly associated with Raynor and structural work by W.H. Taylor and associates.
- (3) Zintl phases AB_2 (e.g. $NaPb_2$).
- (4) $NaTi$ type phases.
- (5) $CuAl_2$ type phases (e.g. Na_3Au , Ge_2Fe , Sn_2Co ; $CuAl_2$ precipitation-hardens aluminium).
- (6) The chi phases of α -Mn structure (e.g. in $Fe-Cr-Mo$ system).
- (7) The β -W type phases.

Ternary I.C.'s can occur even where not occurring in surrounding binary systems. Examples: ($Mg-Ag-Al$) Laves phase; ($Ni-Cr-Mo$) sigma phase. The isomorphy $Co_3Al_2 \rightarrow FeNiAl_2$ instances a theoretically important further aspect of atomic replaceabilities.

Reference should be made also to the theoretical work of Pauling, Hume-Rothery, Raynor, H. Jones, Bernal (explanation of structural stability and bonding in I.C.'s in terms of electron transfer and orbital vacancies), and to Bradley's and Westgren's classical X-ray structural investigations.

See also: Hume-Rothery rule.

Bibliography

- BARRETT C.S. (1943) *Structure of Metals*, New York: McGraw-Hill.
- HUME-ROTHERY W. and COLES B.R. (1954) *Phil. Mag. Suppl.* 3, 149.

HUME-ROTHERY W. and RAYNOR G.V. (1954) *The Structure of Metals and Alloys*, London: The Institute of Metals.

RAYNOR G.V. (1949) *Progress in Metal Physics* I, 1, London: Butterworths.

SMITHELLS C.J. (1955) *Metals Reference Book*, London: Butterworths.

STILLWELL C.W. (1938) *Crystal Chemistry*, New York: McGraw-Hill.

H.J. GOLDSCHMIDT

INTERMOLECULAR FORCES. These are generally of the Van der Waal's type and consequently involve short-range attractive forces, e.g. polarization, resulting from valence electron motions in the atomic constituents of the molecule. They are clearly envisaged from such experiments as the Joule-Thomson effect and the variation of gaseous viscosity with temperature; they must be taken into account when dealing with the equations of state and with phase equilibria. The application of Bose-Einstein statistics indicates that the forces between molecules tend to keep them together, i.e. to produce condensation at an equilibrium distance. If the molecules are brought closer than this, forces of repulsion are brought into play; these arise from the closed electron shells as well as the repelling nuclei.

L. JACOB

INTERMOLECULAR POTENTIAL. The work done in completely isolating two molecules from one another. Equations to describe the potential as a function of the distance between the molecules contain a positive term, representing the repulsion when there is overlap of the closed electron clouds of the two molecules and a negative term, representing the attraction between (1) the oscillating clouds of electrons in the two molecules, (2) asymmetric charge distributions within the molecules and (3) mutually induced charged within the molecules. Several potential energy equations have been put forward; the main ones are called (a) the Sutherland model, (b) the Lennard-Jones potential (c) the Buckingham potential (d) the Buckingham-Corner potential, and (e) the modified Buckingham (6-exp) potential.

W.M. JONES

INTERNAL-COMBUSTION ENGINE. These are defined as heat engines in which a fuel (oil, gas or coal) is burnt with air to form the working fluid; however the indirectly heated gas turbine is usually classed with them, as although combustion is kept separate from the working fluid as in a steam engine, the working fluid has to be compressed in the gaseous state so that as in internal combustion engines, the compression process has to be highly efficient if any net power at all is to be obtained. Internal combustion engines can thus be conveniently divided into (1), piston type in which the process is periodic with air and fuel drawn into the cylinder, compressed, burnt, expanded and exhausted and (2), the continuous gas turbine such as the open circuit, in which air is compressed to p_1 , expanded thermally by combustion

of fuel at nearly constant pressure, then expanded adiabatically in the turbine back to atmospheric pressure, and then exhausted, preferably after cooling in a heat exchanger to the compressed air before combustion.

The simplest piston engine is the spark ignition two stroke, in which the crankcase acts as a low compression ratio pump and the exhaust and inlet valves are both operated by the uncovering of ports by the piston. In this case if the exhaust port opens before the inlet, it must also close after the inlet port whereas ideally it should close before. The 4-stroke spark ignition engine operates on a real cycle approximating to the Otto cycle; in the first downstroke the cylinder fills with air and fuel at atmospheric pressure through a valve—a horizontal line at p_a on the p - v diagram. The upstroke gives adiabatic compression, then the spark gives ignition and combustion at nearly constant volume as the crank passes the top dead centre. Then the adiabatic expansion gives the working downstroke. Near the bottom dead centre the exhaust valve opens and the pressure drops to atmospheric; the subsequent upstroke sweeps the exhaust gases from the cylinder at atmospheric pressure, the other horizontal line on the p - v diagram making a loop of very small area joined to the main working cycle at the lowest pressure point. Apart from a slight finite area of this loop due to irreversible pressure losses, and the change in gas composition due to combustion, the cycle does approximate to a single fluid retained in the cylinder and taken round an Otto cycle. The 4-stroke compression ignition cycle approximates to the composite cycle but again there is an additional loop on the p - v diagram representing drawing in air at atmospheric pressure at the beginning of the cycle and scavenging at the end. Because there is no fuel in the air during adiabatic compression a much higher compression ratio can be used than in the spark ignition engine and the air temperature at the top of the adiabatic compression stroke is high enough to ignite the fuel which is injected as the piston starts to move down in such a way that combustion takes place partly at constant volume and partly at constant pressure. The rest of this stroke provides adiabatic expansion. The open-circuit gas turbine could operate on a cycle which is an approximation to the Ericsson if the compression were carried out nearly isothermally at atmospheric temperature by multiple interstage cooling. If the compressed air was then heated nearly to the working temperature of the turbine blades in a heat exchanger, combustion of the fuel and expansion to atmospheric pressure took place nearly isothermally by having a large number of partial expansions with interstage combustion chambers and finally the heat was given up in the heat exchanger so that the gases were discharged at nearly atmospheric temperature.

Actual gas turbine cycles are usually much simpler than the ideal Ericsson avoiding the complications of a large heat exchanger and intercoolers and reheaters.

They approximate to the Joule cycle. They also have cycles of considerably lower efficiency because of pressure losses in the combustion chamber and ducts and because the efficiencies of the adiabatic compressors and turbines are appreciably less than unity.

In any open circuit gas turbine the combustion products must be greatly diluted with air as the combustion temperature would otherwise be about 2000°C and the turbine blades will only stand about 600°C. Also the gas velocity through them is of the order of thousands of cm/sec whereas laminar flame propagation speeds are of the order of cm/sec. Thus a special type of combustor has been developed in which primary combustion is stabilized by recirculation and is nearly stoichiometric. The walls of the combustion chamber are of heat resisting steel cooled by violent forced convection on the outside to the air which is added further along for dilution. A combustion efficiency of better than 99 per cent can be achieved.

See also: Heat engine.

M. W. THRING

INTERNAL CONSTITUTION OF SUN AND STARS. The main difference between the Sun and other stars is that the Sun is much nearer the Earth and is the only star whose actual shape we can see. All other stars appear to us as point sources of light, and their shapes and sizes have been deduced from their type, apparent brightness, and distance. The interior of the stars is neither visible nor directly accessible to us, and models using theories dealing with their interior conditions are worked out using extrapolations of known physical phenomena. Usually a spherically symmetric distribution is assumed, and the appearance of these models is deduced, then compared with observation. The Sun has a radius of approximately 7×10^{10} cm and a mass of 2×10^{33} g; the radius having been determined by measurement of the distance of the Earth from the Sun and of the angular diameter, and the mass by consideration of the motion of the planets and their distances.

Taking the mass, radius and luminosity of the Sun as units, the stars range from 10^4 to 10^{-2} in mass, from 10^8 to 10^{-2} in radius and from 10^5 to 10^{-3} in luminosity. Thus the Sun is a star of medium type, and the greater observable detail of its surface has allowed complex theories of its atmospheric structure to be formulated. The stars retain their form by the balancing of the inward gravitational forces by forces arising from the radiation pressure of outward flowing energy and from the gas pressure, the fundamental equation of mechanical equilibrium in stellar interiors being

$$\text{grad } P = \rho \text{ grad } \varphi$$

(where P is the total pressure and φ the total potential normally only gravitational). Figures 1 and 2 show the variation of mass, pressure, density, and temperature with radius for a typical star.

Stars are initially composed of mostly hydrogen, which is transformed into helium in the central core.

See Index for location of terms not found in this volume

This nuclear reaction forms energy which is carried from the interior high temperature zone to the surrounding lower temperature zones, in which no nuclear reactions are taking place, by means of either radiation or convection. Finally, at the surface, radiation takes over entirely the rôle of energy transport and pours the energy into space.

Once again taking the Sun's mass and radius as units, the value of the central density of the model given above is about $100 M/R^3 \text{ g cm}^{-3}$ and the central temperature is $2 \times 10^7 M/R^\circ \text{ K}$.

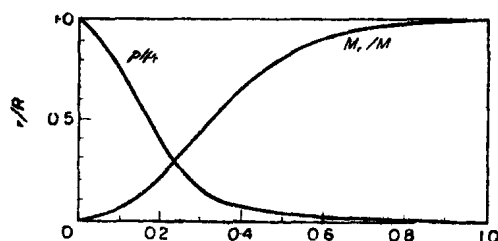


Fig. 1. (Radial distance)/(total radius) against (density)/(total density) and (mass within a sphere of radius r)/(total mass).

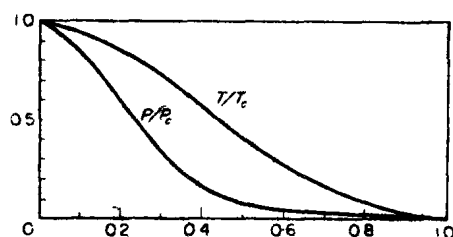


Fig. 2. (Radial distance)/(total radius) against temperature and pressure in units of the central values.

Two types of double stars are known. Optical doubles occur when two stars, separated by great spatial distances, appear to be close when viewed from the Earth, but true double stars are bound to each other by gravitational attraction and orbit around their common centre of gravity. The fission theory of double stars accounts for their presence by the rotational break-up of normal stars, set into fast rotation by a close passage by another star, passage through a dust cloud or gravitational contraction.

Bibliography

- ALLEN C.W. (1955) *Astrophysical Quantities*, London: The University Press.
 FLÜGGE S. (Ed.) (1959) *Handbuch der Physik* Vol. 51, Berlin: Springer.
 JEANS J.H. (1928) *Astronomy and Cosmogony*, Cambridge: The University Press.
 KUIPER G.P. (1953) *The Solar System*, Vol. 1. *The Sun*, Chicago: The University Press.
 LITTLETON (1953) *The Stability of Rotating Liquid Masses*, Cambridge: The University Press.

J.S.GRIFFITH

INTERNAL CONVERSION. Internal conversion is the process in which a nuclear transition, which would otherwise result in γ -ray emission, takes place by imparting the full available energy to one of the electrons in its own atom. The ejected conversion electron then emerges with an energy $E_\gamma - E_B$ where E_γ is the γ -ray energy and E_B is the binding energy of the particular electron. The degree of internal conversion in a particular electron shell is specified by the internal conversion coefficient $\alpha_{K, L, M \dots}$ where

$$\alpha_{K, L, M \dots} = \frac{\text{number of } K, L, M \dots \text{ conversion electrons}}{\text{number of } \gamma\text{-rays}}.$$

This quantity can be calculated exactly from quantum electrodynamics and depends only slightly on the details of nuclear structure.

The calculations are very involved but have now been carried out for a large range of elements and transition energies by Rose, and by Sliv and Band.

As well as being dependent on atomic number, and energy of the γ -ray transition and of course on the electron shell from which the conversion electron originates, the value of the internal conversion coefficient is sensitive to the multipole order and parity change of the γ -ray transition.

The internal conversion coefficients are generally sufficiently different for successive multipole orders to enable the multipolarity to be characterized unambiguously from the measured internal conversion coefficient. In many cases the spin and parity changes involved in the nuclear transition can then be determined. The process therefore has considerable importance in nuclear spectroscopy.

In general if the initial and final nuclear states have angular momenta J_1 and J_2 then the change in angular momentum ΔJ can take on any of the integral values $|J_1 - J_2| \leq \Delta J \leq J_1 + J_2$.

The value $\Delta J = |J_1 - J_2|$, however, determines the multipole order of the most intense component in the radiation field, higher order fields being progressively weaker by a large factor. In the case where $J_1 = J_2$, however, the lowest order multipole is the dipole ($L = 1$).

The parity selection rules require

$$\Delta\pi = (-1)^L \text{ for electric radiation of multipolarity } L$$

$$\Delta\pi = (-1)^{L+1} \text{ for magnetic radiation of multipolarity } L.$$

Mixtures of magnetic and electric radiation of successive orders are often observed together in nuclear transitions, the precise ratio being dependent on nuclear structure. In these cases two conversion coefficients are of course involved in determining the value of ΔJ .

The most generally useful method of measuring internal conversion coefficients is by means of a β -ray spectrometer. The conversion electron lines from different electron shells can then be identified by their energies and their intensity measured. A

supplementary measurement of the intensity of unconverted γ rays is then made by placing in front of the source a heavy element radiator in which the γ rays produce Compton and photoelectrons whose intensity is measured with the spectrometer.

This method is generally applicable even when there is a cascade of γ rays or branching is present in the decay scheme. Often the γ -ray transition is followed or preceded by α or β particle emission in which case it is merely necessary to count these particles to determine the number of γ -rays plus the number of internal conversion processes.

Following internal conversion a vacancy is left in one of the electron shells of the atom. This is filled by an electron dropping in from a higher level and a cascade of characteristic X rays and Auger electrons follows. The yield of X rays is the same as in other processes which create a vacancy in an electron shell, e.g. electron capture or photoelectric absorption, and is specified for a particular electron shell by the fluorescence yield $\omega_{K, L, M \dots}$ where

$$\omega_{K, L, M \dots} = \frac{\text{number of } K, L, M \dots \text{ X rays.}}{\text{number of vacancies in the } K, L, M \text{ shells.}}$$

Burhop has shown that the extensive measurements of this quantity which are available for the K electron shell are in approximate agreement with a formula

$$\omega_K = \frac{1}{1 + a_K/Z^4}.$$

A relation which follows from the fact that the calculated Auger transition rate is practically independent of Z whereas the radiative transition rate varies as Z^4 .

The K series fluorescence yield data is best fitted with $a_K = 1.12 \times 10^6$, giving $\omega_K = 0.5$ at $Z = 33$.

The data available for the three L shells is much less complete but follows a similar relation.

See also: Auger effect.

Bibliography

- BURHOP E. H. S. (1952) *The Auger Effect*, Cambridge: The University Press.
 ROSE M. E. (1958) *Internal Conversion Coefficients*, Amsterdam: North-Holland.
 SLIV L. A. and BAND I. M. (1956, 1958) *Coefficients of Internal Conversion of γ -Radiation*, Moscow, Leningrad: USSR Academy of Sciences.

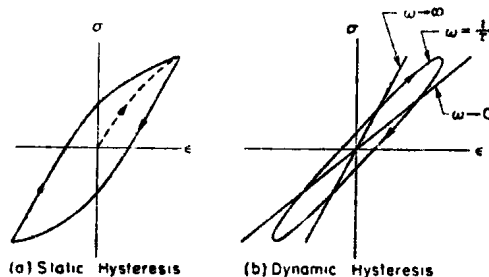
D. WEST

INTERNAL FRICTION. Friction in general is the property of a mechanical system to convert work introduced from outside irreversibly into heat. The term internal friction is used generally for mechanical systems, when this dissipation of energy occurs not only on the surface but throughout the system usually by an atomistic or microscopic process. An internal dissipation of energy can also be caused by magnetic fields in ferromagnetic materials or by electric fields in dielectrics. Although the same or similar dissipative atomistic processes occur, the term magnetic or

dielectric relaxation is used here. Correspondingly internal friction, or damping capacity, is sometimes called mechanical relaxation, although this term is too narrow and describes only part of the internal friction effects. According to the second principle of thermodynamics it is characteristic of all systems showing internal friction that entropy will be produced during a cyclic process.

Internal friction is mainly observed in systems undergoing periodic vibrations and its magnitude can be determined by the decay of free vibrations or of travelling waves in a test sample.

A measure of internal friction is the quantity $\Delta W/W$ where ΔW is the energy loss per cycle and W the total vibrational energy. If σ is the applied



external driving force (stress, pressure, torque) and ϵ the resulting displacement (strain, volume, angle) then ΔW is given by the integral $\int \sigma d\epsilon$ extended over one cycle. Whereas the integral vanishes for an ideal elastic body it will have a finite value if internal friction occurs, because σ and ϵ are then no longer single valued functions of each other. This can be caused in two different ways which are called (a) static hysteresis and (b) dynamic hysteresis, schematically shown in the figure.

In a system showing static hysteresis the application of the external stress will cause a deformation which is at least partly irreversible and will stay after the removal of stress. Hence σ and ϵ are no longer uniquely related to each other (Fig. a). Internal friction of this kind will generally be independent of the frequency of vibrations, but will be strongly dependent on the vibrational amplitude.

In systems showing dynamic hysteresis the application of a stress will cause some reversible, but time dependent, internal rearrangements which allow the deformation to relax to its final value only after a finite time. The behaviour of the sample will then also depend on the rate of change of σ and ϵ and the relation between stress and strain will also contain the first derivatives of σ and ϵ with respect to time. Bodies showing this behaviour are called "anelastic" a term introduced by Zener. In many cases and especially for small vibrations the relation between σ , ϵ , and their time derivatives is linear, then the internal friction is independent of the vibrational amplitude, but it is easily seen that internal friction caused by such inter-

See Index for location of terms not found in this volume

nal relaxations will be dependent on the frequency of vibration. At very high frequencies the internal relaxation has no time to take place and hence the system behaves purely elastically and no energy losses occur. At very low frequencies the system relaxes completely during each cycle and again the system is purely elastic but now its apparent elastic modulus has decreased to some smaller "relaxed" value. At some intermediate frequency ω_m , which has about the value $\omega_m \approx 1/\tau$ where τ is the relaxation time or the time it takes to accomplish the internal rearrangement, a maximum in internal friction will occur because there will then be a phase difference φ between σ and ϵ (Fig. b). Formally this can be described for periodic vibrations by a complex elastic modulus \bar{M} with $\sigma = \bar{M}\epsilon$ and $\bar{M} = M(1 + i\varphi)$.

Although relaxation processes are the most common source of dynamic hysteresis another cause is internal resonance. Here a set of microscopic or atomistic oscillators exists with a characteristic frequency ω_0 . If the external frequency of excitation approaches ω_0 , the oscillators are set in resonance and will dissipate part of their vibrational energy by transferring it into random lattice vibrations or heat. Since the resonance frequency of oscillators of atomic dimensions is usually very high, dynamic hysteresis of this type is mainly observed well above the megacycle range. The difference between relaxation losses and resonance losses is that the restoring force for the internal adjustment is mainly caused by a change of entropy in the first case and by a change of internal energy in the second.

In recent times, internal friction has become an important scientific tool, because it allows a study of certain atomistic processes which could not be observed easily in another way. One of the best known examples is that of an internal relaxation which occurs by thermally activated diffusion of solute atoms in a solid. The relaxation is caused because the solute atoms interact with the applied stress and can jump into certain lattice positions where they can relieve the external stress. The relaxation time τ is here given by $\tau = \tau_0 \exp(-\Delta H/kT)$ where ΔH is the enthalpy of activation for the specific diffusion process. The maximum of the internal friction peak occurs at a frequency ω_m when $\omega_m \tau = 1$ or when the external frequency of excitation is of the order of the average jump frequency of the atoms in the relaxation process. According to the above equation ω_m will increase with increasing temperature and from a shift of ω_m with temperature it is in principle possible to obtain the value of ΔH . However, in more complicated cases when several processes contribute to internal friction a whole spectrum of relaxation times will exist and the interpretation then becomes more difficult.

A general phenomenological treatment of relaxation processes is possible with the methods of the thermodynamics of irreversible processes (Meixner). For each system there exists for given external conditions a

state of thermal equilibrium where the free energy $G = H - TS$ has its minimum. By variation of some external parameters the equilibrium can be changed and the approach to a new equilibrium state for small deviations can be described by a system of linear differential equations. By solving these with the appropriate boundary conditions one obtains general information about the behaviour of the system. The practical value of this method is, however, limited due to the fact that the solution often contains parameters which are unknown and cannot easily be obtained by measurements.

A more direct method for describing relaxation phenomena involves the application of statistical mechanics. Here an atomistic model is used directly and the change in atomic distribution caused by external forces is studied. The difficulty here is that often the atomic process is not completely understood or that the correlation between the measured macroscopic property and the atomistic process can be very complicated.

There exists a wide variety of different frictional mechanisms depending on whether internal friction takes place in gases, liquids, polymers, amorphous or crystalline solids. In the dissipation process external energy is finally converted by some coupling mechanism into energy of random lattice vibrations in solids or into kinetic energy of atoms in gases. A direct coupling between external applied stress and lattice vibrations exists for instance in solids known as thermoelastic effect and the heat flow between parts of the body which are under different stresses during vibration gives rise to internal friction. In other cases, the dissipation occurs by some intermediate processes. For instance, it may be due to magneto-mechanical coupling (magnetostriction) in ferromagnetic solids the applied stress produces a change in internal magnetization which can give rise to a static hysteresis or which can cause eddy-currents which in turn produce heat by electric losses. Other mechanisms which can be sources of internal friction are electromechanical coupling (piezoelectric effect), chemical reactions, exchange or resonance-processes in molecules, direct atomic rearrangements in solids by stress induced ordering or plastic deformation.

By far the most extensive investigations of internal friction has been made in crystalline solids and especially in metals and many of the important effects have been explained and reviewed by Zener and more lately by Nowick. The contributions of dislocations has been reviewed by Lücke and Granato. Much less understood are the frictional phenomena in polymers which usually show a complicated viscoelastic behaviour (Alfrey, Eirich). In most cases only a phenomenological description in terms of macroscopic viscosity coefficients is possible. Internal friction or sound-absorption in gases has been treated by Kneser and in fluids Markham *et al.*

See also: Anelasticity. Damping.

Bibliography

- ALFREY T. (1948) *Mechanical Behaviour of High Polymers*, New York: Interscience.
- EBRICH R. E. (1956, 1958) *Rheology*, Vol. I, II, New York: Academic Press.
- KNESER H. O. (1949) *Ergebn. der Exakt. Naturwiss.* **22**, 121.
- LÜCKE K. and GRANATO A. (1957) in *Dislocations and Mechanical Properties of Metals* (J. Fisher, Ed.), New York: Wiley.
- MARKHAM J. J., BEYER R. T. and LINDSAY R. B. (1951) *Rev. Mod. Phys.* **23**, 353.
- MEIXNER J. (1954) *Thermodynamik der irreversiblen Prozesse* (collected reprints): Aachen.
- NOWICK A. S. (1953) *Progress in Metal Physics*, Vol. IV, (B. Chalmers, Ed.) New York: Interscience.

G. SCHÖCK

INTERNAL PRESSURE. The derivative $(\partial U/\partial V)_T$ is sometimes called the internal pressure (usually of a liquid) since the relation

$$(\partial U/\partial V)_T = T(\partial p/\partial T)_v - p,$$

sometimes called the thermodynamic equation of state, can plausibly be thought of in the form internal pressure = thermal pressure — external pressure. The concept has been used particularly by J. H. Hildebrand and his followers in the study of non-electrolyte solutions.

See also: Melting (pressure) curve. Van der Waals equation of state.

M. L. MCGLASHAN

INTERNAL STRAINS, EFFECT OF, ON MAGNETIC PROPERTIES. The presence of internal strains in a ferromagnetic makes the material harder magnetically as well as mechanically. The strains may usually be removed by some form of heat treatment.

K. J. STANDLEY

INTERNUCLEAR DISTANCE, EQUILIBRIUM. Symbol r_e . The distance apart between two chemically bound atoms at the equilibrium position of vibration. Obtained from diffraction techniques or from the fine-structure analysis of molecular spectra. Of the order of Ångström units (10^{-10} m).

See also: Atomic radius. Interatomic distance. Ionic radius.

H. E. HALLAM

INTERNUCLEAR DISTANCE FROM MOLECULAR SPECTRA. The internuclear distance or equilibrium separation r of a diatomic molecule may be derived from observations of the rotation spectrum. The separation of neighbouring lines is given by $h/2\pi cI$ cm $^{-1}$ and the moment of inertia I is μr^2 , μ being the reduced mass of the molecule.

A. DALGARNO

INTEROCULAR DISTANCE. Distance between the rotation centres or the perspective centres of the eyes (approximately 65 mm).

INTERPLANAR SPACING (CRYSTALLOGRAPHY). The spacing between adjacent members of any family of crystal planes drawn through the three-dimensional atomic structure of a crystal. These spacings, which are of the order of 1 Å in magnitude, can be determined very accurately by X-ray diffraction methods.

G. E. BACON

INTERPOLATION. Interpolation, perhaps the most fundamental branch of numerical analysis, has been aptly described as "reading between the lines of a mathematical table". It is essentially the process of replacing a function $f(x)$ whose value is given at only a finite number of values of the argument x , by a continuous function $F(x)$ which is equal, or very nearly equal, to $f(x)$ at those points. This interpolating function $F(x)$ can then be used to provide estimates of $f(x)$ at intermediate points.

The simplest example of an interpolating function is the formula for linear interpolation. This effectively approximates the graph of $f(x)$ between two consecutive arguments x_0 and x_1 by the chord joining its end points, and is given by

$$F_p = f_0 + p\Delta f_0 \quad (0 \leq p \leq 1),$$

where $F_p \equiv F(x_0 + ph)$, $f_0 \equiv f(x_0)$, $h = x_1 - x_0$, and where Δf_0 is the first forward difference of f_0 , defined by $\Delta f_0 = f_1 - f_0$.

In many published tables the interval h has been chosen small enough for the error resulting from this formula to be negligible. Limitations on space, however, often prohibit the provision of a linearly interpolable table, and it is then necessary to use a more complicated formula. In certain cases $F(x)$ might be chosen to be a rational function, or a series of trigonometric functions. Usually, however, the advantages of using a polynomial interpolating function are overwhelming, and a table user will do so unless the tablemaker has recommended a superior procedure which depends on the properties of the particular function.

Tables with equal intervals of argument. In most published tables of functions of a single variable, the argument proceeds at equal intervals, and the interpolation polynomial is then available in several different forms. The simplest extension of the linear formula to a polynomial of general degree n is provided by the Newton forward formula, namely

$$F_p = \left\{ 1 + p\Delta + \binom{p}{2}\Delta^2 + \dots + \binom{p}{n}\Delta^n \right\} f_0,$$

where $\Delta^s f_0 = \Delta^{s-1} f_1 - \Delta^{s-1} f_0$, and $\binom{p}{s} = p(p-1) \times (p-2) \dots (p-s+1)/s!$. This formula can be remembered conveniently as the generalization of the operational relation $f_1 = (1 + \Delta)f_0$ into the form $f_p = (1 + \Delta)^p f_0$.

The Newton formula, although simple in form, and sometimes useful for interpolating near the end of a

table, is not usually convenient in practice; the coefficients $\binom{p}{s}$ have to be evaluated, and forward differences $\Delta^s f_0$ are often not immediately available. More satisfactory formulae can be devised by rearrangement of the Newton formula. The most obvious rearrangement is probably the *Lagrange* formula. If Δf_0 is replaced by $(f_1 - f_0)$, $\Delta^2 f_0$ by $(f_2 - 2f_1 + f_0)$ and so on, the result is the *Lagrange* interpolation polynomial, given by

$$F_p = L_0 f_0 + L_1 f_1 + \dots + L_n f_n,$$

where L_s is a polynomial in p of degree n . This formula has the attraction that no differences are required, so that if tables of the coefficients L_s are available, an interpolation can be performed quite readily. It has the serious disadvantage, however, that there is no clear indication from the formula as to how many terms should be used, whereas the user of the Newton formula, for example, sees his terms becoming progressively smaller, and truncates the series when the next few terms are clearly negligible.

More satisfactory than either of these forms for most purposes are formulae involving *central* differences, defined by

$$\begin{aligned}\delta f_{1/2} &= f_1 - f_0, & \delta^2 f_0 &= \delta^{2s-1} f_{1/2} - \delta^{2s-1} f_{-1/2} \\ \delta^{2s-1} f_{1/2} &= \delta^{2s} f_1 - \delta^{2s} f_0,\end{aligned}$$

so that $\Delta^s f_0 = \delta^s f_{s/2}$. The values of the differences are often set out in the following pattern, in which any quantity is obtained by subtracting the upper from the lower of the two quantities to its left.

$$\begin{array}{llll}x_0 & f_0 & \delta f_{1/2} (= \Delta f_0) & \delta^2 f_0 (= \Delta^2 f_{-1}) & \delta^3 f_{1/2} (= \Delta^3 f_{-1/2}) \\x_1 & f_1 & \delta f_{3/2} (= \Delta f_1) & \delta^2 f_1 (= \Delta^2 f_0) & \delta^3 f_{3/2} (= \Delta^3 f_0) \\x_2 & f_2 & \delta f_{5/2} (= \Delta f_2) & \delta^2 f_2 (= \Delta^2 f_1) & \\x_3 & f_3 & & & \end{array}$$

Examination of the coefficients $\binom{p}{n}$ in the Newton formula shows that the most effective range of application will be round about $p = n/2$, since here the last included terms will be at their smallest. This suggests that more convenient forms of the interpolation polynomial might be obtained by rearranging the Newton formula in terms of function values and central differences, given in a form suitable for the range $0 \leq p \leq 1$, and the most common is the *Bessel* interpolation formula

$$\begin{aligned}F_p &= f_0 + \{p\delta + B_2(p) 2\mu\delta^2 \\ &\quad + B_3(p)\delta^3 + B_4(p) 2\mu\delta^4 + \dots\} f_{1/2},\end{aligned}$$

where $2\mu\delta^2 f_{1/2} = \delta^2 f_0 + \delta^2 f_1$, and where $B_n(p)$ is a polynomial in p of degree n . The odd differences in this formula can each be replaced by even differences,

using $\delta^{2s+1} f_{1/2} = \delta^{2s} f_1 - \delta^{2s} f_0$, and this gives rise to the *Everett* interpolation formula, namely

$$\begin{aligned}F_p &= \{(1-p) + E_2(p)\delta^2 + E_4(p)\delta^4 + \dots\} f_0 \\ &\quad + \{p + F_2(p)\delta^2 + F_4(p)\delta^4 + \dots\} f_1,\end{aligned}$$

where $E_n(p)$ and $F_n(p)$ are polynomials in p of degree $(n+1)$. To use either of these formulae conveniently, tables of the coefficients $B_n(p)$, or of $E_n(p)$ and $F_n(p)$ must be available. Such tables, and many other useful coefficients and formulae, are given in "Interpolation and Allied Tables", henceforth referred to as I.A.T.

Other arrangements, including some relevant to the range $-\frac{1}{2} \leq p \leq \frac{1}{2}$, are possible, and these are also given in I.A.T. Generally, however, the Bessel and Everett formulae are the most useful central difference forms, particularly the latter because it does not need odd differences.

The power of the central difference formulae can be greatly increased by the use of what is known as *throw-back*. This is a device which incorporates some of the fourth difference term with the second, and arose from the observation that $\{B_4(p) + C B_2(p)\}$ can be made small throughout the range $0 \leq p \leq 1$ if the constant C is suitably chosen. If the table-maker provides, with the function values, a column of "modified" second differences, defined by $\delta_m^2 = \delta^2 - C\delta^4$, the user can interpolate with the formula

$$F_p = \{(1-p) + E_2(p)\delta_m^2\} f_0 + \{p + F_2(p)\delta_m^2\} f_1,$$

provided the *fourth* differences do not exceed 1000 units in the last figure, with no more labour than would be required to use the unmodified formula in a table with fourth differences less than 20, and with negligible loss of accuracy. Powerful throw-back formulae used in published tables are given, with the necessary coefficients, in I.A.T.

The original interpolation polynomial of degree n which appears in the various forms of Newton, Lagrange, Bessel and Everett, is that polynomial which coincides with the function values at $(n+1)$ successive tabular arguments. When the throw-back device has been used, however, this coincidence is no longer satisfied, and a new basis for polynomial interpolation must be established. This may be found in the solution of the problem of *optimum* polynomial interpolation; that is, the problem of finding the polynomial of lowest degree which represents $f(x)$ in a given tabular interval to a specified accuracy. If $f(x_0 + ph)$ is expanded in a series of *Chebyshev* polynomials and truncated, a polynomial is obtained whose deviation from the best possible is negligible for practical purposes. The most suitable formula for the usual range $0 \leq p \leq 1$ is

$$F_p = f_0 + a_1 T_1(\xi_s) + a_2 T_2(\xi_s) + \dots + a_n T_n(\xi_s),$$

where $\xi_s = (1 + \cos \pi/2s)p - \cos \pi/2s$ and $T_s(\xi_s) = \cos(s \cos^{-1} \xi_s)$, so that $T_s(\xi_s) = 0$ when $p = 0$.

The rearrangement of this in the form

$$F_p = f_0 + c_1 p + c_2 p^2 + \dots + c_n p^n$$

gives a convenient and powerful interpolation formula. If the table-maker gives the coefficients c_p alongside the function values, the user can interpolate quickly without having to use tables of interpolation coefficients. The only disadvantage of this formula compared with one using modified differences is that the table may occupy more space; this space may be recovered, however, by increasing the argument interval, which often increases the degree of the interpolating polynomial only slightly.

Many formulae, including those involving throwbacks, can be obtained by rearrangement of such Chebyshev-type expansions. One of them, of similar power to the Everett formula which uses modified second and fourth differences, is

$$F_p = q \{1 + (1 - q^2)(d_2 + q^2 d_4)\} f_0 \\ + p \{1 + (1 - p^2)(d_2 + p^2 d_4)\} f_1$$

where $q = 1 - p$ and where d_2/f and d_4/f are coefficients given in the table alongside the function values. This seems preferable to the similar Everett formula since it can, if necessary, be evaluated much more easily without using tables of coefficients; it is, however, more troublesome to the user than the straightforward economized polynomials given above.

Nevertheless, tables which provide modified differences are so common that the formulae involving them will continue to be used.

Another interpolation aid sometimes provided is a set of *reduced derivatives*. Alongside f are provided hf' , $\frac{1}{2!} h^2 f''$, $\frac{1}{3!} h^3 f'''$ and so on, where h is the argument interval, and where primes denote differentiation with respect to the argument. These quantities are the coefficients of the powers of p in the Taylor expansion of $f(x_0 + ph)$ about $p = 0$, and are used in the same way as the coefficients c_p of the economized polynomial.

Inverse interpolation. The problem of finding x , given a value of $f(x)$, frequently arises; it is easily solved using any of the preceding interpolation formulae by isolating the term linear in p and replacing the estimate F_p by the known f_p . For example the Everett formula using modified second differences is used in the form

$$p = \frac{1}{f_1 - f_0} \{f_p - f_0 - E_2(p) \delta_m^2 f_0 - E_2(p) \delta_m^2 f_1\}.$$

If the terms in δ_m^2 are neglected, this gives an approximate value of p which is used to calculate $E_2(p)$ and $F_2(p)$. With these inserted in the formula, a better approximation to p is evaluated, which in turn is used to give better values of $E_2(p)$ and $F_2(p)$. Such an iterative procedure rapidly produces the required p , and hence $x = x_0 + ph$.

Functions of two variables. The usual procedure for interpolating a function of two variables is to inter-

polate first in one variable, at tabular values of the other which enclose the given point. A further single interpolation then produces the desired result. However, existing double-entry tables invariably provide adequate instructions for the user, and these should be followed.

Unequal intervals. There sometimes arises the problem of interpolating in a function given at unequally spaced values of the argument. This problem could be tackled by using the appropriate form of the Lagrange formula, but since the arguments are unequally spaced the coefficients will not often be found in any table and must be computed. Because of this, and of the other disadvantage of the Lagrange formula already noted, this method is usually rejected in favour either of a divided-difference formula, or of iterative linear interpolation.

In the former case, a difference table is constructed with the arguments x_i in ascending order as in the equal-interval case, but with the following adjustments. A convenient 'interval' h , approximately equal to the total range divided by the number of intervals, is chosen. The differences, known as "adjusted divided differences" are defined as follows,

$$\delta f_{1/2} = \frac{h}{x_1 - x_0} (f_1 - f_0),$$

$$\delta^2 f_0 = \frac{2h}{x_1 - x_{-1}} (\delta f_{1/2} - \delta f_{-1/2}),$$

$$\delta^{2n+1} f_{1/2} = \frac{(2n+1)h}{x_{n+1} - x_{-n}} (\delta^{2n} f_1 - \delta^{2n} f_0),$$

$$\delta^{2n} f_0 = \frac{2nh}{x_n - x_{-n}} (\delta^{2n-1} f_{1/2} - \delta^{2n-1} f_{-1/2}).$$

This definition is such that the differences reduce to ordinary central differences when the argument interval is a constant, equal to h . The interpolation polynomial can again be written in several different forms. Probably the most convenient here is that of Gauss, namely

$$F_p = \left\{ 1 + \frac{(x - x_0)(x - x_1)}{h^2 2!} \delta^2 \right. \\ + \frac{(x - x_{-1})(x - x_0)(x - x_1)(x - x_2)}{h^4 4!} \delta^4 + \dots \left. \right\} f_0 \\ + \left\{ \frac{x - x_0}{h} \delta + \frac{(x - x_{-1})(x - x_0)(x - x_1)}{h^3 3!} \delta^3 + \dots \right\} f_{-1/2}.$$

The method of iterative linear interpolation is a way of calculating values of the interpolation polynomials of successive degrees which provides an indication of the stage at which enough terms have been used. If $f_{a,b,c,\dots,j,k}$ is the value at x of the interpolation polynomial which takes the values f_a, f_b, \dots, f_k at x_a, x_b, \dots, x_k respectively, then $f_{a,b,c,\dots,j,k} = [(x_k - x)f_{a,b,c,\dots,j} - (x_a - x)f_{b,c,\dots,j,k}]/(x_k - x_a)$.

The usual arrangement of the numbers is as follows

x_0	$x_0 - x$	f_0	$f_{0,1}$		
x_1	$x_1 - x$	f_1	$f_{1,2}$	$f_{0,1,2}$	
x_2	$x_2 - x$	f_2	$f_{2,3}$	$f_{1,2,3}$	$f_{0,1,2,3}$
x_3	$x_3 - x$	f_3			

where, for example,

$$f_{0,1,2} = ((x_2 - x) f_{0,1} - (x_0 - x) f_{1,2}) / (x_2 - x_0).$$

The interpolation is assumed to be correct when successive values in the same column have a negligible difference.

This method is simpler to use than divided differences for an isolated interpolation, but since it requires a new table for each value of x it compares unfavourably when several interpolates are needed.

Interpolation for a high-speed computer. The preceding methods have been discussed from the point of view of a desk-machine user. If a high speed electronic computer is available, the use of auxiliary tables of interpolation coefficients, and indeed of finite differences themselves, is inconvenient. Briefly, the interpolation aids which seem best suited to such a computer are economized polynomials, which may be of high degree to cover a large range, and iterative linear interpolation where an orthodox table must be used. Non-polynomial interpolating functions may, however, often be used with advantage; it is also a common practice to compute an algebraic function afresh for each argument.

A full discussion of the error committed in using the basic interpolation formulae will be found in, for instance, Buckingham's "Numerical Methods".

See also: Finite differences. Integration, numerical. Mathematical tables. Numerical analysis.

Bibliography

- BUCKINGHAM R. A. (1957) *Numerical Methods*, London: Pitman.
 HILDEBRAND F. B. (1956) *Introduction to Numerical Analysis*, New York: McGraw-Hill.
 KOPAL Z. (1955) *Numerical Analysis*, London: Chapman and Hall.
Interpolation and Allied Tables (1956) London: H. M. Stationery Office.
 N. P. L. (1956) *The Use and Construction of Mathematical Tables*. Mathematical Tables Vol. 1, London: H. M. Stationery Office.
 N. P. L. (1961) *Modern Computing Methods*. Notes on Applied Science, No. 16, London: H. M. Stationery Office.

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INTERSECTED POINT, TOPOGRAPHICAL. A point whereof the position is fixed by theodolite intersections from two or more other points, but which itself is not occupied by the theodolite.

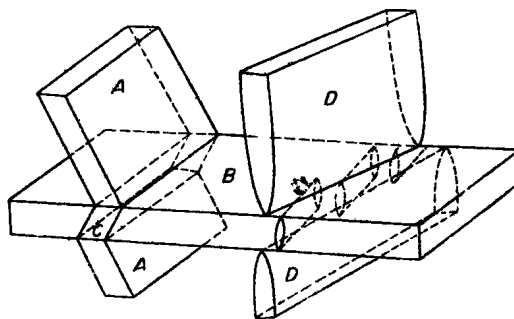
G. BOMFORD

INTERSECTION OF METALLIC TWINS. Mechanically induced twin lamellae in certain metals are sometimes observed to run through each other. Such intersections can be classified into perfect and imperfect intersections. The figure illustrates a perfect intersection. Here the crossing twin A and the crossed twin B are each in twinned orientation relative to the parent crystal, while the secondary twin C is twinned relative to the lattice in B . For a perfect intersection to take place, it is necessary that:

(1) The traces of A and of C in the twinning (lamella) plane of B must be parallel to each other.

(2) The direction and magnitude of shear must be the same in A and C .

Condition (1) represents the necessity for A and C to join up accurately over large areas of A , and condition (2) represents the necessity for the strains, created by the twinning shears of A and C , to match.



Geometry of twin intersections:
 A, B, C — perfect intersection
 D, B — imperfect intersection

When B , as is usual, is a twin of the "first kind" (i.e. when the twinning plane of B has rational Miller indices), these two laws reduce to the single requirement that the shear directions in A and C should be parallel to each other and therefore to their line of intersection. This line is indicated by the arrow in the figure. Perfect intersections of this kind have been observed in iron and in uranium.

When B is a twin of the "second kind" (the twinning plane does not have rational Miller indices) the analysis is more complex, and perfect intersections are not normally expected. One type of perfect intersection for this case has however been recorded in uranium.

Imperfect intersections sometimes arise when one or both of the above requirements fail to be observed. The appearance of such intersections is normally distinguishable from the pattern indicated in the figure on the left, and resembles more nearly the "pinched-off" configuration shown at the right of the figure (lamella D). Imperfect intersections have been observed in zinc, tin, titanium and uranium. When twin lamellae are very thin, it is difficult to distinguish an intersection from a situation where the mechanical impulse of the impinging twin on an