cycle repeating until the oven completes its operating program.

The rated power output of household microwave ovens ranges from 350 to 750 W. It is unlikely that higher-powered ovens will be produced for household use because of the power limitations associated with the ordinary electric outlet. Ovens rated at 750 W consume all the power permitted to be drawn under existing electrical codes. The rated power is the power that is delivered to a large load in the microwave oven cavity (for example, 0.5 gal or 2 liters of water). The power delivered to a small load such as a bag of popcorn or a single food item can be much less, down to one-half of the rated power.

Heating uniformity. The microwave power is introduced into the oven cavity through or in association with a mechanism that improves the heating uniformity. The heating-uniformity problem basically stems from the fact that the wavelength of the microwave energy (4.82 in. or 12.24 cm) is large compared to oven cavity dimensions. This means that the oven cavity has standing-wave mode patterns leading to areas of intense high microwave heating and associated areas of light microwave heating. To make the heating more uniform, the oven has a rotating mechanism at the point where the microwave energy enters the cavity, which causes the mode patterns to occupy different positions, thus providing for more uniform heating of the product over a period of time. Other ovens have a rotating product platform that causes the product to be moved through the regions of high and low microwave heating so that it will be uniformly heated over a period of time. While the microwave power generally comes into the top of the oven cavity, newer designs have the power coming in from the sides, rear, or bottom of the oven cavity and in some cases introduced in two places simultaneously.

Shell design and cavity size. Oven designs differ with respect to the shelf that the product rests on. For a long time, shelves were always microwave-transparent and were made of either glass or ceramic. Newer oven designs incorporate wire racks or metal shelves or metal turntables. The type of shelf has an effect on the heating characteristics of different food products. The wire racks and metal shelves give relatively poor performance with frozen products and products that use interactive packaging, such as those with partial shielding and special inserts that cause crisping or browning.

The size of the oven cavity also has an influence on performance characteristics, particularly uniformity of heating. Oven cavities at the present time range from 0.4 to 1.5 ft³ (0.01 to 0.04 m³) for countertop microwave ovens, up to 3.5 ft³ (0.10 m³) for wall-type built-in ovens. The larger the cavity, the larger the number of mode patterns that can exist within the cavity, and generally speaking the easier it is to achieve uniform heating.

Safety features. All ovens have special interlock circuitry to make sure that they cannot be operated with the door open. By federal regulation, this interlock circuitry includes a backup interlock which senses whether or not the primary interlock is operating properly. If an attempt is made to operate the microwave oven with the primary interlock disabled or damaged, the interlock monitor will cause a fuse contained within the oven to fail, preventing further operation until the oven has been serviced.

The door of the oven is subject to a special set of design requirements and contains microwave circuits that control to a safe level the leakage of microwave energy between the surface of the door and the microwave oven cavity. The door and its interlock circuitry must be designed to withstand 100,000 operations without maintenance or failure.

In the United States, the safety features of a microwave oven are regulated by three agencies: the Federal Communications Commission, which imposes standards to prevent the operator from being exposed to harmful radiation; the Federal Communications Commission, which imposes regulations to protect the public from being exposed to other electronic equipment; and the Underwriters Laboratory, which has established a set of standards designed to keep the microwave oven from being a fire or electrical hazard. As a consequence of these regulatory constraints, the microwave oven is one of the most reliable and safe appliances on the market today.

For background information see Magnetron; Microwave in the McGraw-Hill Encyclopedia of Science & Technology.


Molecular collisions

Many new experiments have been conducted in which molecules and atomic orbitals are aligned or oriented with polarized laser light in order to investigate the geometrical effects of collisions. The alignment and orientation of molecules and orbital electron clouds can critically control chemical reactivity and the transfer of energy between species. Theoretically it is well known that the directions of orbitals strongly affect chemical bonding; the energetics for different geometrical approaches of molecules are also thoroughly explored by calculations.

Only recently, however, have experimental methods become sufficiently well developed to allow researchers to probe directly the effects of orbital geometries and angles of approach. The methods utilize polarized laser light, or sometimes focusing electric fields, to align or orient orbital electron...
clouds or molecular species before the collision and to interrogate the geometries of products after collisions. These geometrical effects can influence the types of product species and states that are formed, as well as the rates of reactions and energy transfer. A new field of collision dynamics highlights the vector properties of collisions and dynamical stereochemistry.

**Alignment and orientation.** The terms alignment and orientation describe different anisotropic spatial distributions of the electron clouds or molecular frameworks. The terms pertain to the mathematical formulation of the distributions of angular momentum vectors which describe the electron orbitals or the rotating molecules. The direction of an angular momentum vector is perpendicular to the plane of rotation of the particles. In a spherically symmetric, isotropic, random distribution, all spatial directions are populated with equal probability, and there is no alignment or orientation.

Alignment refers to an angular momentum distribution that is symmetric about the center of mass. A good physical example of alignment is a dumbbell-shaped $p$ orbital that is vertically aligned in the laboratory frame of reference. The horizontal alignments are missing from the initial random distribution of possible orbital directions. The plane of rotation of a molecule may also be aligned, with both clockwise and counterclockwise rotations contributing equally. Orientation refers to an angular momentum distribution which is asymmetric with respect to the center of mass. Physical examples of orientation include molecules which have been selected to rotate only clockwise or counterclockwise with respect to the observer or molecules which have two different ends with one end preferentially pointing toward the observer.

**Polarized laser radiation.** Anisotropic angular momentum distributions in atoms or molecules may be produced or interrogated by linearly or circularly polarized light. Typically, linearly polarized light is used to prepare or access aligned states of atoms or molecules for collision experiments and circularly polarized light to produce oriented distributions. In addition, aligned or oriented distributions often emit polarized radiation, which is detected through polarization filters and used to infer the geometrical stereochemistry of the process. Although early experiments on the depolarization of emission by collisions were carried out with lamps, lasers provide the high intensity of light and wavelength selectivity required to excite or interrogate large numbers of atoms and molecules for difficult and elegant experiments in dynamical stereochemistry.

An excellent example of a stereochemical effect without collisions is illustrated by the simple breaking of a chemical bond with a laser. Polarized laser light is used to excite deuterated methyl iodide (CD$_3$I) to break the carbon–iodine bond by photodissociation. A second laser is used to ionize the deuterated methyl radical fragments (CD$_3$) after the particles have had time to travel on their initial trajectories for a short distance following the dissociation. The ions are then accelerated by an electric field and strike a flat microchannel plate and phosphor screen. Figure 1 displays one of the resulting two-dimensional images of the pattern of fragments as they escape from the center of the dissociation zone. The dumbbell-shaped pattern shows the spatial anisotropy when one particular alignment of parent molecules is dissociated. The pattern is directly related to the fact that the linearly polarized laser preferentially dissociates only those molecules which lie parallel to the laser polarization. The methyl group end of the molecule is randomly oriented in either direction along the polarization direction, producing two lobes of fragment intensity. The sharpness of the angular pattern indicates that the molecules dissociate in a time that is short compared to the time for rotation of the methyl iodide. Additional experiments demonstrate that the deuterated methyl radicals are also aligned after the dissociation; that is, the plane of rotation is preferentially selected, having a distinct memory of the direction of the broken bond.

**Energy transfer.** One of the simplest collision processes involving alignment effects is the transfer of energy from one electronically excited state of an atom to another upon collision with a rare gas atom. An excited singlet $p$ state of a calcium atom is prepared with pure alignment by excitation with linearly polarized light from a pulsed laser. In a crossed-beam configuration, the excited calcium atom collides with a helium rare gas atom, and energy transfer takes place to a triplet $p$ state of slightly lower energy. If an initial perpendicular alignment of the singlet $p$ state is chosen, this results in a more attractive potential force between the calcium and helium atoms, whereas the parallel orbital alignment is more repulsive. The
Molecular collisions

Fig. 2. Raw alignment data for the calcium singlet $p$ energy transfer to a triplet $p$ state upon collisions with helium. The amplitude of the triplet $p$ fluorescence is monitored as a function of the angle of laser polarization $\phi$, which aligns the initial singlet $p$ state. Traces are also shown for the laser off and for the laser on, but target (helium) gas off. (After W. Busser, D. Neuschäfer, and S. R. Leone, The effect of orbital alignment on the forward and reverse electronic energy transfer Ca(4sSp $^{1}P_{3}$) + M = Ca(4sSp $^{3}P_{2}$) + M with rare gases, J. Chem. Phys., 87:3833–3842, 1987)

attractive state crosses more favorably through the region of the lower-energy triplet $p$ state potentials, giving it a better chance to undergo the energy transfer process. Thus, when the laser prepares the perpendicular configuration preferentially, there is a greater chance that the collision will result in a transfer from the singlet to the triplet state.

Figure 2 shows the dramatic dependence of the energy transfer probability on the angle of laser polarization. The signal intensity owing to the energy transfer varies by a factor of 1.6 as the initial orbital angle is rotated. After transformation from the laboratory angle to the collision frame of reference, it is found that the perpendicular alignment is favored, as expected from the potential interactions. In a variety of new experiments, the orbital symmetries and potential curves that are responsible for energy transfer processes are being identified for the first time. The laser alignment method is able to act like a scalpel to interrogate the geometrical details of these processes.

The intrinsic values of the alignment effects are most likely much greater than the observed values, which typically fall between 1 and 2 for the ratio of probabilities. This is because, in the experiments, not all orbitals approach in a pure perpendicular or parallel configuration. Figure 3 shows a schematic of a typical orbital trajectory that might occur. The orbital is initially prepared in the parallel configuration, but as the two atoms collide, the orbital points partially toward the helium atom and precesses owing to angular momentum and potential forces. Thus, the trajectory does not result in a pure parallel configuration throughout the collision, and the overall alignment effect is diminished. Theoretical work is being carried out, with excellent success, to determine the intrinsic effectiveness of the orbital alignments on the collision process.

**Reaction dynamics.** One of the most exciting aspects of alignment and orientation is their effect on chemical reactivity. The rates of formation of particularly electronically excited states of the calcium chloride (CaCl) product in the reaction of excited calcium atoms with chlorine and hydrogen chloride are strongly influenced by the initial orbital alignment of the calcium atom. Collisions between two excited sodium atoms in their $p$ states lead to a reaction forming the sodium dimer ion. By using two polarized laser beams, all the different dumbbell orbital alignments can be probed, such as when both orbitals are end-on, both orbitals side-on, or one orbital end-on and one side-on. When the two orbitals are end-on, the largest reaction probability is observed at high collision velocities.

A high degree of alignment can be achieved in some molecular species by selective photodissociation of the undesired alignments with a high-powered laser. In this way, reactions of excited xenon atoms with selected planes of the iodine monobromide (IB) molecule are tested, and it is determined that the reactivity is enhanced when the plane of the molecule is parallel to the reagent direction of approach. Some...
molecules can be oriented by hexapole electric fields. The classic reaction between an atom such as rubidium and methyl iodide (CH₃I) to form rubidium iodide (RbI) is strongly inhibited when the rubidium atom stacks the methyl (CH₃) end. The reaction of barium with nitrous oxide (N₂O) prefers attack on the end of the molecule with the oxygen atom. The fluorescence from the barium oxide (BaO) product is also partially polarized when the end with the oxygen atom is approached, but not when the end with the nitrogen atom is approached first. This suggests that the atoms must slide around to the appropriate end before reacting, thus scrambling the alignment of the barium oxide product.

Information which suggests that the alignment of molecular orbitals is involved in the transition states of chemical reactions is obtained by spectroscopic measurements of the lambda doublet components of the product molecules and also by using polarized laser light to interrogate the final plane of rotation of the product molecules. In this way, the reaction of translationally fast hydrogen atoms with oxygen (O₂) molecules is found to occur in a planar configuration in which both the lone electron on the hydroxy (OH) product and the plane of rotation of the hydroxyl radical are confined to the collision plane.

Collisions with surfaces. The scattering of molecules at various angles off surfaces can result in both orientation and alignment. The plane of rotation of both nitric oxide (NO) and nitrogen (N₂) molecules becomes aligned after scattering collisions with a smooth silver surface. In some circumstances, the molecules can tumble like a football end over end, resulting in orientation so that only a clockwise or counterclockwise rotation is detected with respect to the observer looking from the side. Molecules desorbing from a surface are also probed to determine whether they leave the surface doing cartwheels or as a helicopter blade, in which the plane of rotation is parallel to the surface. In one example of nitric oxide on a platinum surface, even though the molecule binds to the surface standing up vertically, the desorption process results in a helicopter motion of the nitric oxide in the gas phase. This result suggests the existence of some weakly bound state in which the nitric oxide is parallel to the surface just before desorption.

For background information see Molecular beams; Molecular orbital theory; Polarized light; Scattering experiments (atoms and molecules) in the McGraw-Hill Encyclopedia of Science & Technology.

Stephen R. Leone


Molecular recognition

A huge variety of biochemical processes are constantly occurring in a living organism. The cells continuously produce proteins, nucleic acids, and scores of other molecules, and process thousands of molecules that enter the organism. Molecules constantly undergo interactions with each other in which bonds are made and broken. Given the numerous processes, it would appear that activity is chaotic. In fact, the extraordinary specificity and selectivity of molecular interactions are characteristic of all biological systems and are the very basis of life. There is very little margin for error when a nucleic acid replicates or codes for a protein or when an antibody recognizes and renders harmless an invading foreign body. An absolute prerequisite to such specificity is the process of molecular recognition.

Immune system. The immune system is primarily a recognition system that protects the living organism from the large numbers of invading microorganisms. The specialists of the immune system are the group of white blood cells called lymphocytes. Two distinctive types, the T cells and the B cells, differ in their activity, but the key to this activity in either case lies in the molecular structure of the cell surface. Both invading microorganisms and lymphocytes have specific coupling sites on their surfaces, areas displaying a distinctive three-dimensional geometry and character. The sites on the invader are called the antigen epitopes, and those on the lymphocytes the antibody receptors, which, in the case of the B cell, are the immunoglobins. If the receptors on a B cell fit the antigens on a bacterium sufficiently closely, as a key fits a lock, then the B cell will adhere to the surface of the invader and will be stimulated to produce more antibodies of the same shape. T cells have analogous recognition pathways; in addition, they possess the remarkable property of recognition of self.

Noncovalent forces. Molecular mating, such as discussed above, is triggered by weak chemical forces. Conventional chemistry is concerned primarily with covalent and ionic bonding forces. Covalent bonding arises from sharing and redistribution of the atomic electron density between atoms. Hydrocarbons, for example, are made up of carbon and hydrogen atoms covalently bonded to each other. Ionic bonding is a result of electrostatic interactions between ions, such as in a sodium chloride lattice. However, these forces form only a small part of the molecular repertoire. Noncovalent forces dominate interactions between molecules through their sheer number, even though they are weaker in magnitude. These forces can be classified as charge-dipole, dipole-dipole, and dispersion forces, and the entropically driven hydrophobic forces. The weak forces of the first kind stem from interactions between nonbonded, partially charged atoms in molecules. These partial charges are really