based resource industry to a dynamic and innovative global industry will require a multidisciplinary effort, involving the industry itself; technology developers and equipment manufacturers; educators and researchers together with other research organizations, centers, and institutions; governments; and international mining organizations and societies.

Such a multidisciplinary effort will create a business environment where new technologies can enjoy economical justification and support. The coordinated efforts of the mines, technology developers and manufacturers, and academic and research organizations will foster a technological environment where research and development is well focused, with a high degree of adaptability to innovation, competitiveness, and the productivity plans of the mines. At the same time, academia will educate and train the future mining work force. Working together with government will balance legislation encouraging mining innovation and application with issues related to the environment and human resources.

For background information *see* AUTOMATION; HUMAN-MACHINE SYSTEMS; INTERNET; MINING; REMOTE-CONTROL SYSTEMS; ROBOTICS; SATELLITE NAVIGATION SYSTEMS; SURFACE MINING; UNDERGROUND MINING in the McGraw-Hill Encyclopedia of Science & Technology.

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Bibliography. G. R. Baiden and E. Henderson, LHD Tele-operation and guidance—Proven productivity improvement tools, *CIM Bull.*, pp. 47–51, October 1994; R. Burgelman, M. Maidique, and S. Wheelwright, *Strategic Management of Technology and Innovation*, 2d ed., Irwin Publishers, 1996; Mining adds $524 billion to the US economy, *Min. Eng.*, pp. 16, September 1997; M. Scoble, Canadian underground mine automation: Progress and issues, *CIM Bull.*, pp. 29–32, January 1996; M. Sopko, Mining's impact on Canadian economy, *13th Mine Operators Conference*, Sudbury, Ontario, Canada, February 16–19, 1997; N. Vagenas, M. Scoble, and G. Baiden, A review of the first 25 years of mobile machine automation in underground hard rock mines, *CIM Bull.*, pp. 57–62, January 1997; J. White and L. Zoschke, Automating surface mines, *Min. Eng.*, pp. 510–511, June 1994.

Molecular cooling

The ability to cool and trap atoms has led to a renaissance in atomic physics. Workers in the field of chemical physics are looking for ways to apply atom-cooling techniques to molecules. Molecular cooling will make it possible to study molecular collisions in a regime where the wave properties of the molecules are dominant as described by quantum chemistry. Molecular cooling may also allow the testing of fundamental theories of physics.

Temperature. The temperature of a gas is related to the velocity distribution of the molecules that make up the gas. By lowering the temperature of the gas, the velocity spread is decreased. In a conservative system, the number-density of a group of particles and its temperature are coupled through Liouville's theorem; lowering of the temperature can be accomplished only by an accompanying decrease in density. The number of molecules per position interval (density) and velocity interval (temperature) is called the phase-space density. This is the quantity defining the number of cold collisions in a gas and determines, for instance, the onset of Bose-Einstein condensation. Techniques that lower the temperature of a gas and lead to an increase of the phase-space density are referred to as real cooling to distinguish these techniques from those that lower the temperature at the expense of density only. One very powerful and general method to cool a gas is by letting it expand through a nozzle into a vacuum, resulting in a dramatic decrease in the rotational, vibrational, and translational temperature. In a pulsed supersonic expansion, a beam can be produced with a high density (typically 10^{13} molecules per cubic centimeter) and a very narrow velocity distribution at a low associated temperature (typically around 1 kelvin). This expansion results, however, in a large absolute velocity and thus a high temperature in the laboratory frame. By using time-varying electric fields, the average velocity of the molecules in the laboratory frame can be lowered, thus making the low temperatures obtained in a molecular beam available in the laboratory frame.

Molecular beam deceleration. Although neutral as a whole, polar molecules do interact with electric fields as the charge is not distributed homogeneously over the molecules (one end of the molecules is more positively charged and the other end is more negatively charged). This charge separation leads to a dipole moment. The interaction of the dipole moment with an external electric field is known as the Stark effect. Depending on the orientation of the molecule with respect to the electric field, which is an inherent property of its quantum state, a molecule is attracted (a so-called high-field seeker) to or repelled (a so-called low-field seeker) from a high electric field. Static electric fields have been used to deflect and focus polar molecules since the 1920s. In the 1950s, it was realized that time-varying electric fields could be used to change the longitudinal velocity of polar molecules. A molecule in a low-field-seeking state will decelerate upon entering an electric field. If the electric field is greatly reduced before the molecule has left the electric field, it will not be accelerated when exiting the field, keeping its lower velocity. This process may be repeated by letting molecules pass through multiple pulsed electric fields. Molecules can thus be slowed down and eventually brought to a total standstill. This can be considered as the neutral analog of a charged particle accelerator. In this process, the phase-space density remains constant; the cooling has taken place in the supersonic expansion.

Comparison with other methods. In the 1990s, much progress was made in gaining control over the motion of neutral atoms, as demonstrated by the realization of Bose-Einstein condensation and the atom laser. These developments were made possible by the use of laser cooling, a technique in which atoms are cooled by many consecutive absorption-emission cycles, leading to a significant momentum transfer from the laser to the atom. Laser light acts as a friction force, damping the motion of the atoms, thereby increasing the phase-space density. Unfortunately, laser cooling requires a "simple" energy level structure, excluding most atoms and all molecules. Therefore, molecules have long been disregarded in cooling and trapping experiments. In 1998, thirteen years after the first atoms were trapped, two different methods were demonstrated to cool and trap molecules. The first method uses collisions with a cold helium buffer gas to thermalize the molecules, after which they are trapped in a magnetic trap. In preliminary experiments, 10^8 calcium monohydride molecules were trapped at a temperature of 400 mK. If the buffer gas can be removed sufficiently fast, it will be possible to cool the molecules further by evaporation. This method is generally applicable to any paramagnetic molecule or atom. In the second method, the molecules are directly formed from laser-cooled atoms, thus avoiding the problems associated with molecular cooling altogether. The so-formed dimers can be trapped in the focus of an intense laser beam. An exciting new development is to apply this laser-association technique to an atomic Bose-Einstein condensate. These two methods are restricted to paramagnetic molecules and (mixed) alkali-dimers, respectively. Deceleration of molecular beams using time-varying electric fields can be used to cool and trap polar molecules.

Applications. Lowering the velocity of molecules increases the time scale on which the molecules can be studied, and thus the accuracy of the measurement. Ultimately, all spectroscopy is limited by the time that the molecules spend in the measuring apparatus. Therefore, cooling molecules to the millikelvin regime increases the measurement accuracy by orders of magnitude. Besides studying molecular structure in detail, this might also be useful for studying fundamental physics. Molecules are currently being used to study time reversal, chirality, and other fundamental physics theories. Another goal is to study the collisional properties of cold molecules. At very low temperatures, the associated de Broglie wavelength of the molecules becomes larger than the classical length of the intermolecular bonds. Therefore, the classical picture of colliding marbles must be replaced by a total quantum-mechanical description of the collision. Studying cold collisions may therefore open up an entire new field in chemistry. Another interesting topic is the study of the mutually interacting electric dipoles. At low temperature, the translational energy is comparable to the dipole-dipole interaction energy. It may be possible to observe the formation of a dipolar crystal analog to the occurrence of ionic crystals in ion traps.

Decelerating and trapping polar molecules. A pulsed molecular beam is formed by expanding a mixture of ammonia and xenon in a vacuum (Fig. 1). Due to rotational and vibrational cooling, only the lowest quantum states of ammonia are populated in the beam. In a second vacuum chamber, the ammonia molecules are slowed down from 260 m/s to 13 m/s (853 ft/s to 43 ft/s) using a Stark decelerator consisting of 63 deceleration stages. The deceleration stages are formed by two 3-mm-diameter (0.12-in.) rods spaced 2 mm (0.079 in.) apart. The electrodes are connected to four switchable power supplies delivering a voltage of either 10 or −10 kV (Fig. 2).

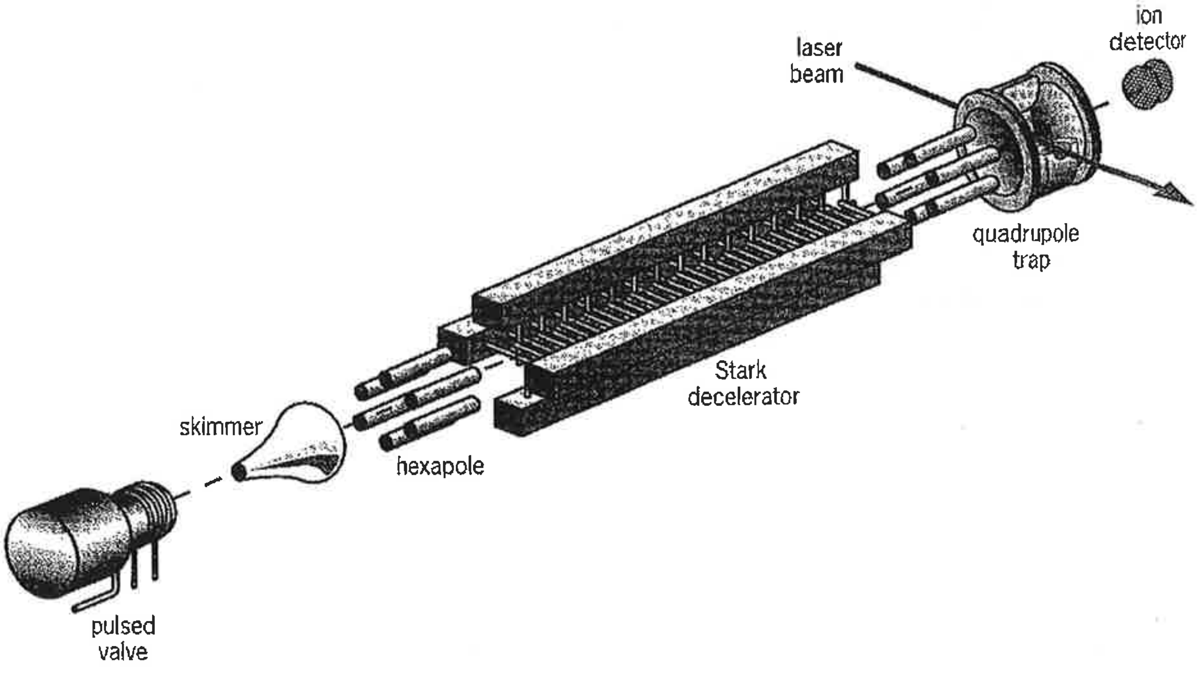

Fig. 1. Apparatus for Stark deceleration. (*After H. L. Bethlem et al., Electrostatic trapping of ammonia molecules, Nature, 406:491–494, 2000*)

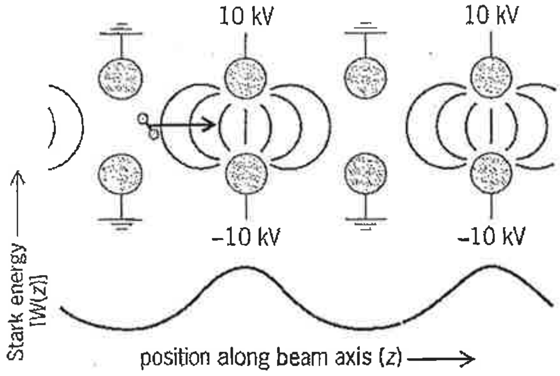

Fig. 2. Scheme of Stark deceleration. The electrode configuration is shown together with the potential (Stark) energy of a molecule as a function of its position along the molecular beam axis. (*After H. L. Bethlem et al., Trapping neutral molecules in a traveling potential well, Phys. Rev. Lett., 84:5744–5747, 2000*)

The computer-controlled pulsers switch the electric fields synchronously with the bunch of decelerated molecules. This decelerated bunch is focused using a hexapole lens into a electrostatic quadrupole trap formed by a ring electrode and two end-cap electrodes. By initially applying an asymmetric voltage to the end caps, the molecules are decelerated upon entering the trap. When the molecules are brought to a standstill near the center of the trap, the voltages are switched to create a symmetric electric field with a minimum at the center of the trap. The molecules are attracted to this minimum and have insufficient energy to escape from it. The depth of the potential well in which the ammonia molecules are then confined is 350 mK. The trapped molecules are monitored by shining in a pulsed laser beam. Densities of trapped ammonia molecules of 10^6/cm^3 at temperatures below 350 mK have been observed, with higher densities and lower temperatures anticipated for the near future—the ultimate limitation being only the phase-space density of the initial beam. At present, the ammonia molecules can be observed up to 1 second after loading the trap, limited by collisions with background molecules. This method will work for any polar molecule, including molecules that are highly relevant from a chemical perspective, such as H_2O and OH. Once these molecules are trapped at sufficiently high density, they can be further cooled by evaporation, opening the way to study them at unprecedentedly low temperatures. Cold collisions can also be studied using a crossed molecular beam setup. The ability to tune the molecular beam velocity allows collision cross sections to be determined as a function of the collision energy. Recent theoretical work has predicted that this cross section will have rather narrow resonance at low energy, caused by long-lived transition states in the collision complex. Studies of this resonance will give information complementary to that provided by conventional spectroscopy of these complexes.

For background information *see* BOSE-EINSTEIN STATISTICS; DIPOLE MOMENT; LASER COOLING; LOW-TEMPERATURE PHYSICS; MOLECULAR BEAMS; PARTICLE TRAP; STARK EFFECT; STATISTICAL MECHANICS in the McGraw-Hill Encyclopedia of Science & Technology.
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Bibliography. J. T. Bahns, P. L. Gould, and W. C. Stwalley, Formation of cold ($T \leq 1$ K) molecules, *Adv. Atom. Mol. Opt. Phys.*, 42:171–224, 2000; H. L. Bethlem et al., Electrostatic trapping of ammonia molecules, *Nature*, 406:491–494, 2000; B. Goss Levi, Hot prospects for ultracold molecules, *Phys. Today*, pp. 46–50, September 2000; J. A. Maddi, T. P. Dinneen, and H. Gould, Slowing and cooling molecules and neutral atoms by time-varying electric-field gradients, *Phys. Rev. A*, 60:3882–3891, 1999; J. D. Weinstein et al., Magnetic trapping of calcium monohydride molecules at millikelvin temperatures, *Nature*, 406:148–150, 1998.

Molecular rheology

The friction between two moving surfaces, such as a piston in an automobile engine and the cylinder surrounding it, is routinely reduced by a lubricant between the surfaces. The viscosity of a lubricating fluid is determined by measuring the force (per unit area) of the surface required to maintain the surfaces moving at a constant relative speed: the higher this force, the higher the viscosity (**Fig. 1**). Another way to determine viscosity is to measure the terminal speed with which a metal sphere falls through a column of the fluid: the lower the terminal speed, the higher the fluid's viscosity. Viscosity thus measures a fluid's ability to resist flow. Clearly, water is much less viscous than motor oil, which in turn is much less viscous than a typical polymer melt (such as polyethylene). Moreover, the viscosity of a typical polymer decreases as the shear rate (the ratio of the relative velocity of the two moving surfaces to the distance between them) increases, which is known as shear thinning. Shear thinning behavior is an example of non-newtonian behavior. Ultimately, the differences in the viscosity of these fluids must reflect differences in the shape of the molecules in the fluids and the forces between the molecules. For example, polymer molecules are long and can become entangled, thus

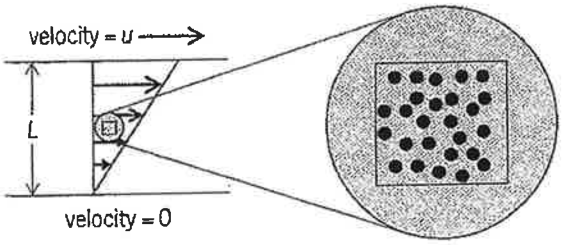

Fig. 1. Schematic of shearing motion. The lubricating fluid is sheared between the upper surface moving at velocity *u* relative to the lower surface. The surfaces are separated by a distance *L*. The shear rate is *u*/*L*. The force per unit area of the surface required to maintain this steady state is called the shear stress, and the viscosity is the ratio of the shear stress to the shear rate.