prototype monitor three light-emitting diodes light up sequentially if the monitor is (i) operational, (ii) a toxic hazard is present and (iii) a dangerous hazard exists and the area should be evacuated. Condition (iii) triggers a high-pitch alarm. Preliminary tests indicate that these sensors could make valuable fire detection systems.

To make the ceramic element more selective, we have identified over 300 new sensor materials. These have all been screened for their ability to sense common flammable and noxious gases (CH_4, O_2, CO, CO_2, C_2H_4, C_3H_8, NH_3, NO_2, Cl_2, SO_2 and H_2S). This database contains materials which are broad-spectrum gas sensors as well as materials that respond selectively to particular gases. Combining the output signals from a multiple array of sensors based on different materials provides a degree of selectivity.

We are currently researching a different route for improved sensor performance, based on the fact that the response of a semiconducting oxide gas sensor can be modified in a controllable way by changing the geometry of the sensor components. The resistance change in the presence of carbon monoxide depends critically on the electrode spacing and on the thickness of the ceramic element. Effectively, as the gas reacts on the ceramic, concentration profiles are established within the sensor body that depend upon the diffusivity and oxidation kinetics of the gaseous species. The conductivity measurement can be made at a point which samples only a section of this concentration profile and the geometry of the sensor element can be tailored so that, for example, more reactive gases are consumed totally before they reach the detector electrodes. Consequently, only the less reactive constituents of a gas mixture are detected.

As well as the ceramic layer thickness and electrode spacing, the sensor response also depends on the nature of the gas, the properties of any metal catalyst and the temperature. In principle, an array of devices can be generated in which individual outputs have known relationships to one another for different gases. These known relationships can then be used to detect and compensate for drift, ageing and poisoning of the sensor elements. Extending these concepts further, a single sensor device can be designed that consists of layers of different oxide materials of different thicknesses interconnected by electrodes of different spacings. Multilayered ceramic structures can be fabricated easily using ceramic–plastic forming technology, for example.

One can also envisage a methodology for the fine-tuning of gas-sensitive resistors to specific applications: these go way beyond fire detection to environmental monitoring, combustion control, vehicle engine management, process control, medical diagnostics and industrial plant monitoring. □

Laser cooling the atom of atoms

From **Dieter Meschede** in the Institut für Quantenoptik, Universität Hannover, Germany

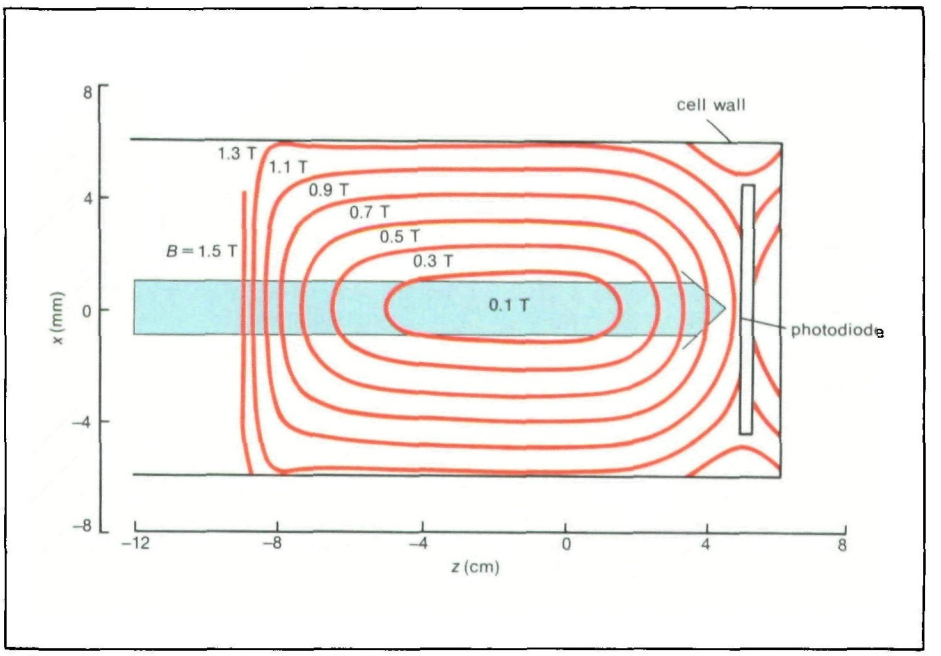
EXPERIMENTS with atomic hydrogen are widespread because hydrogen is the simplest and theoretically most accessible atom. This is not only true for isolated atoms, but also for spin-polarised gases of cold hydrogen. In this unique system, in which the total spins of all the hydrogens are parallel, the atoms only interact in one of the large number of possible molecular potentials. This potential (known as $^3\Sigma$) does not allow bound states, leading to the expectation that spin-polarised hydrogen remains gaseous down to zero kelvin. But the lack of a suitable laser source for cooling hydrogen has prevented experimenters investigating the wealth of new physics expected at these temperatures.

It is predicted, for example, that at high densities and below a certain temperature, T_0, a finite number of particles will occupy the zero energy state of the system; that is, spin-polarised atomic hydrogen will undergo a Bose–Einstein phase transition. Such a degenerate quantum system, in which wave properties are more prominent than particle properties, has not been observed to date. For currently available densities, $\approx 10^{14}$ cm^{-3}, Bose–Einstein condensation is expected in the 10 μK regime. Efficient cooling schemes are necessary to achieve this goal, so the demonstration of laser cooling of atomic hydrogen by Jook Walraven and collaborators at the University of Amsterdam is an important step forward (D Setija *et al. Phys. Rev. Lett.* (1993) 70 2257).

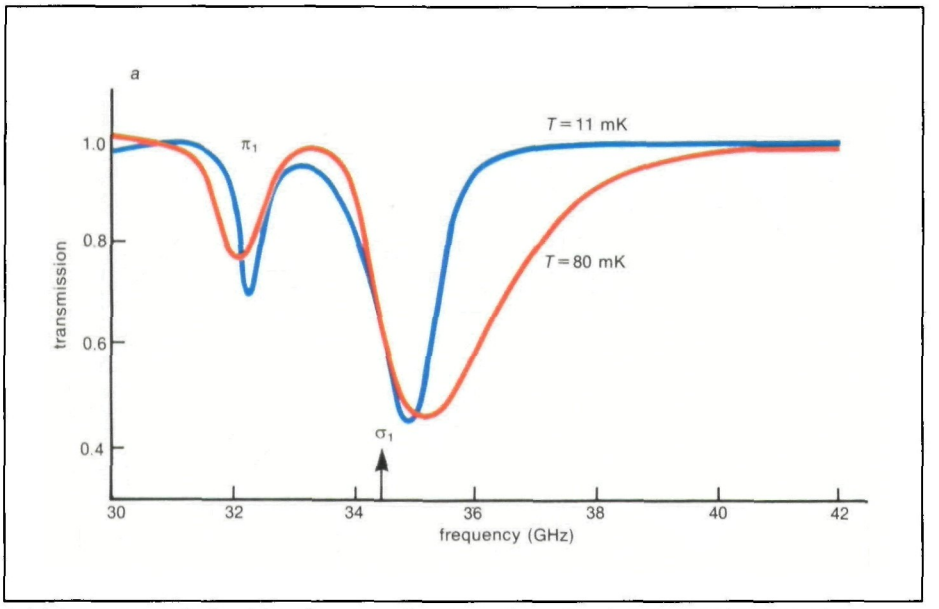
Over the past five years laser cooling and trapping of neutral atoms has become almost commonplace in quantum optics and atomic physics laboratories. Moreover, these powerful experimental methods have scored remarkable successes, such as the observation of extremely-low-temperature gases, localisation of atoms below the wavelength scale, and direct accumulation of cold atoms from the gas phase. In most experiments the lowest temperature currently available (typically a few μK) is limited by the so-called recoil limit – the residual kinetic energy (or temperature) of the atoms corresponds to the momentum imparted by the emission or absorption of a single photon from the cooling lasers.

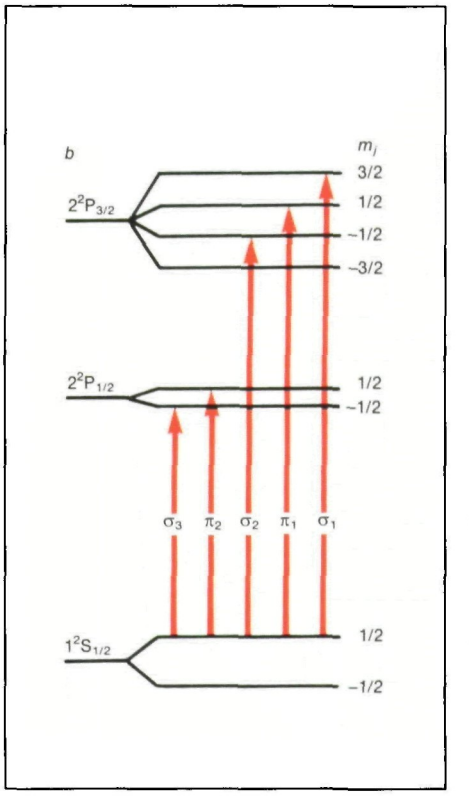
Regrettably hydrogen, the atom of atoms, is not easily manipulated by these techniques due to the lack of suitable light sources. Now the Amsterdam group has succeeded in constructing just such a source, a laser system which supplies sufficient numbers of 121 nm photons (in the vacuum-ultraviolet) to efficiently excite the Lyman-α (1s–2p) resonance of atomic hydrogen. In the apparatus 15 mJ pulses are generated at a wavelength of 365 nm, and a repetition rate of 50 Hz, from an excimer-pumped dye laser system through frequency-doubling. This light is converted into Lyman-α radiation, with an efficiency of 10^{-7}, by frequency-tripling in a krypton/argon mixture. The duration of these pulses, which contain 3×10^9 photons, is 10 ns.

However, the atoms must be trapped before they can be cooled. Hydrogen atoms have a magnetic moment given by the



1 Schematic of a magnetic trap for hydrogen showing contours of equal magnetic potential (red). Spin-polarised hydrogen atoms are confined to the centre of the trap where the magnetic field is a minimum. The cooling laser is shown in blue





2 (*a*) Laser transmission intensity versus frequency through spin-polarised hydrogen in a magnetic trap before (red) and after (blue) laser cooling. The width of the absorption features is a measure of the temperature. The sample was Doppler-cooled using radiation on the red wing of the σ_1 transition (arrow). (*b*) Energy levels in the 1s–2p transition in hydrogen (left). In the $2^2P_{1/2}$ level the intrinsic spin and orbital angular momentum of the electron are antiparallel; in the $2^2P_{3/2}$ level they are parallel. In an external magnetic field each level is split into magnetic substates labelled m_j (right). The only stable trapping ground state is $m_j = 1/2$ with electron and proton magnetic moments parallel; all five allowed transitions from this substate are shown (red)

vector sum of the intrinsic magnetic moments of the proton and electron, and the orbital magnetic moment of the electron. In inhomogeneous magnetic fields this total moment causes a dipole force toward lower fields when it is oriented antiparallel to the local field direction. Figure 1 shows a schematic drawing of the Amsterdam trap and lines of equal magnetic potential: a strong linear magnetic quadrupole field provides confinement in the transverse direction; dipole coils with parallel orientation prevent escape in the longitudinal direction. The magnetic fields act like an oval bottle for cold hydrogen gases at temperatures well below 1 K, and on extended timescales only doubly polarised atoms (electronic and nuclear spin parallel) survive. The atoms are then cooled by irradiation with the 121 nm source in the longitudinal direction.

Doppler cooling relies on the loss of atomic momentum as a consequence of radiative absorption and re-emission from red-detuned counter-propagating laser beams. It becomes inefficient at, or below, velocities for which the Doppler shift equals the natural line-width of the cooling transition. The temperature corresponding to these velocities is called the Doppler limit. Since trapping times of the order of hours are available in the Amsterdam experiment, the atoms can be cooled with a pulsed laser in spite of its low duty cycle. The traditional Doppler cooling method is further modified in this case because it is applied to an optically dense sample in which laser radiation is only absorbed in the outer fringes. Overall cooling of the sample is nevertheless obtained because elastic collisions redistribute the kinetic energy; this redistribution is also necessary because the laser cooling is only active in one direction. Over a 15-minute cooling period a temperature reduction from 80 mK to about 11 mK is observed, accompanied by compression of the sample. However, the temperature remains above the free-space Doppler limit of 2.4 mK due to multiple scattering events.

By scanning the frequency of the cooling laser around 121 nm, it is also possible to record the 1s–2p absorption spectra for hydrogen (figure 2*a*). In all, five transitions contribute to this spectrum (figure 2*b*) but only two are shown in figure 2*a*. These absorption spectra are not very interesting in their own right, but they offer a powerful, non-destructive probe for the temperature and density of the hydrogen sample (O J Luiten *et al. Phys. Rev. Lett.* (1993) **70** 544). This information is encoded in the line shape (temperature) and line strength (density) of the observed spectra. The motion of atoms gives rise to a Doppler shift in the transition frequency which broadens the natural line width, and from which the temperature of the sample can be inferred.

The high optical density has allowed for yet another method of cooling capable of reaching temperatures below the Doppler limit. At the outer fringes, atoms with higher binding energies with respect to the magnetic trapping potential are preferentially excited and, therefore, the lower-energy particles at the core are shielded from radiation. The excited atoms may be ejected from the sample altogether by using a transition (the σ_2 transition, for example) to an excited state from which the atom can decay to the unbound $m = -1/2$ substate of the ground level. This removal of "hot" atoms is equivalent to the well known thermodynamic evaporation cooling scheme in which one lets fast energetic atoms escape across a barrier. Although atoms from the sample are lost in the process, a cooler gas at higher density is left and hence the approach to the quantum regime is continued.

Conventional evaporation cooling has already been used by Thomas Greytak, Daniel Kleppner and colleagues at MIT to access the μK regime (J M Doyle *et al. Phys. Rev. Lett.* (1991) **67** 603). The Amsterdam group have reached 3 mK with the new method, which they call light induced evaporation (LIE), and μK temperatures may soon also be possible. This opens up the possibility of an additional, optical route towards the realisation of degenerate quantum gases.□

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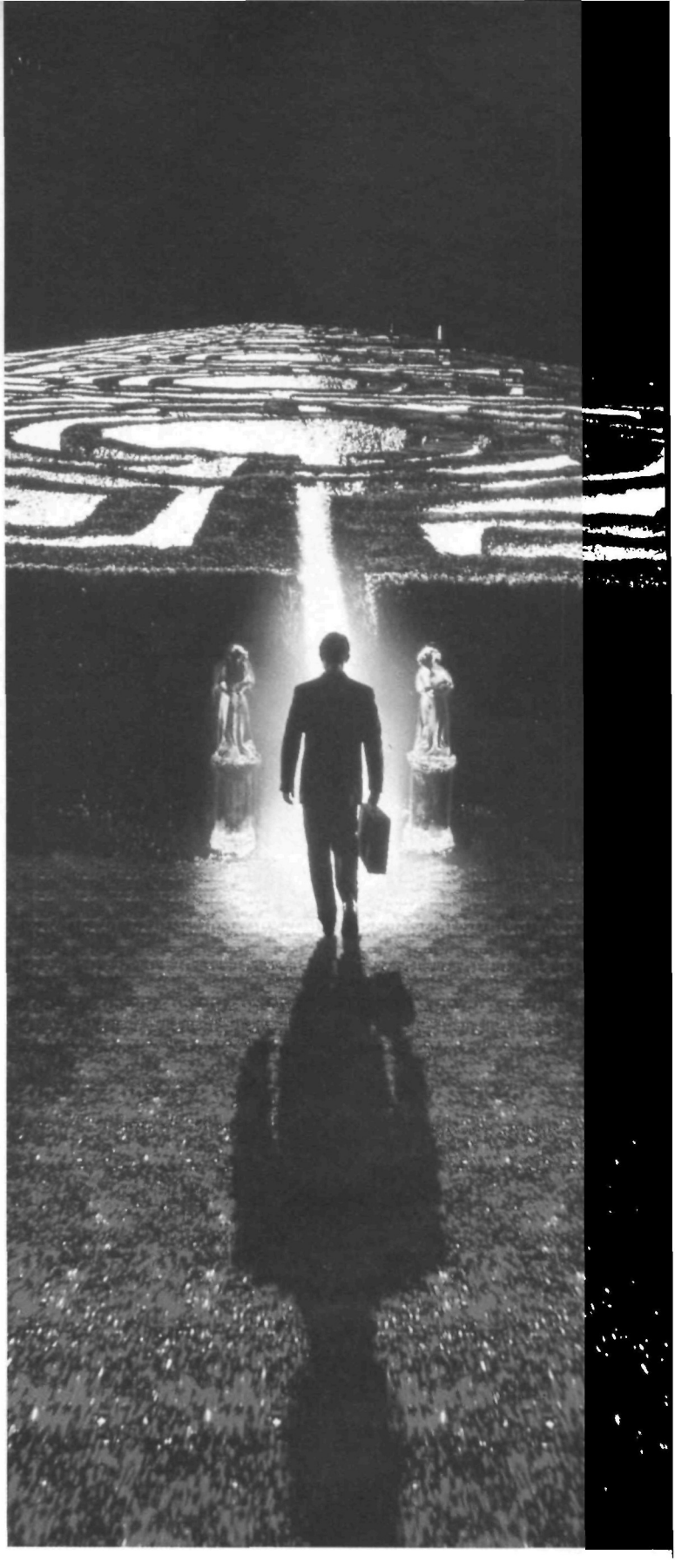

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