hydrogen, both very small effects compared with the (optical or ultraviolet) transition frequency. As a demonstration of the power of their new technique, they report improvements of several orders of magnitude over previous measurements of this isotope shift.

The key feature is the ability of the laser spectroscopist to overcome the Doppler broadening of spectral lines. The monochromaticity of the laser allows selective excitation of atomic excited states. At the same time the laser intensity is high enough for non-linear absorption effects to be exploited: one of these is saturated absorption. A laser beam, with a linewidth much less than the Doppler width of the spectral line of interest, interacts not with all atoms in the absorption cell, but with a set of atoms with resonance frequencies (and therefore velocities) in a narrow range around the laser frequency. An intense beam of laser radiation will excite this set of atoms: it saturates the gas medium and burns a "hole" in the velocity distribution of ground-state atoms. In saturated absorption spectroscopy the output of a laser is split into a weak probe beam and a stronger, chopped saturating beam of the same frequency which are sent in nearly opposite directions through the absorbing gas. If the laser frequency is close to an atomic resonance frequency, the saturating beam bleaches a path for the probe and decreases its absorption, but only for that group of atoms with effectively zero velocity along the laser beampath. Moving atoms see the two beams as of different frequencies, and no such bleaching occurs. In this way the Doppler effect is almost eliminated. The saturation spectrum is obtained by varying the laser frequency and recording the change in the weak probe beam due to the inhomogeneous saturation created by the strong bleach beam. The theoretical limit to the linewidth is then governed by the natural lifetime of the excited state.

A second technique to eliminate Doppler broadening is to use two-photon absorption. This time the laser is split into two counter-propagating beams of equal intensity. This may be achieved merely with a mirror at one end of the cell to reflect the incident light back down the cell. If the laser frequency ω is approximately one-half of an atomic resonance frequency ω_0, an atom can be excited by the absorption of two photons, one from each oppositely travelling wave. An atom of laboratory velocity v sees, in its rest frame, two beams of frequency $\omega(1 - v_x/c)$ and $\omega(1 + v_x/c)$. At resonance, $\omega_0 = \omega(1 - v_x/c) + \omega(1 + v_x/c) = 2\omega$, independent of the velocity of the atom. Therefore Doppler broadening is eliminated if the atom absorbs two photons propagating in opposite directions, and again the natural lifetime of the excited state is the limiting factor in the linewidth. The two-photon absorption

signal has contributions from all atoms in the cell, irrespective of their velocities. This technique also makes possible Doppler-free spectroscopy of s→s or s→d transitions, not possible by one-photon saturated absorption.

Hänsch and his co-workers have simultaneously used two-photon absorption and saturated absorption Doppler-free spectroscopy in their hydrogen work.

A pulsed dye laser output at ~ 4,860 Å in 10 ns pulses of linewidth 120 MHz, is split into two beams. Noting that the crude Bohr theory predicts that the $n = 1-2$ interval is four times larger than the $n = 2-4$ interval, they contrive to frequency-double one beam (so that its wavelength is now ~ 2,430 Å) and excite the $1S_{1/2}-2S_{1/2}$ Lyman-α transition at 1,215 Å in a cell of hydrogen or deuterium atoms, by two-photon absorption. Since an isolated atom in the $2S_{1/2}$ state has a lifetime of ~ 0.14 s this transition could potentially be measured to very great accuracy. At the same time the second beam is used in a saturated absorption spectrometer to measure the $2P_{3/2}-4D_{5/2}$ transition interval at 4,860 Å in a separate cell. By varying the laser frequency, therefore, both transitions can be simultaneously recorded. The measurements are not made in the vacuum ultraviolet, liquid air cooling of the discharge and the use of large gratings is avoided, yet great accuracy is possible.

If the Bohr theory were correct, the two observed transitions would occur at exactly the same dye-laser frequency. The

fact that they are displaced is due to quantum electrodynamic effects (principally the Lamb shift of the various levels), relativistic effects, and partly to nuclear structure effects. The measured displacement between the two transitions gives directly information about the size of these effects without the need for absolute wavelength calibrations or an ultraprecise value of the Rydberg constant. By comparing the experimental and theoretical line separations, Hänsch *et al.* deduce a 1s Lamb shift of 8.20 ± 0.10 GHz for H, and 8.25 ± 0.11 GHz for D, which agree within their error limits with the theoretical values. At the same time they obtain a 1s–2s isotope shift in atomic hydrogen and deuterium of 670.933 ± 0.056 GHz, in fair agreement with the theoretical value, but representing an improvement of several orders of magnitude over previous (traditional pre-laser) measurements. To appreciate the leap in accuracy made possible by Doppler-free laser techniques, this measured isotope shift should be compared with the hydrogen Lyman-α line Doppler width of ~ 6 GHz.

To strike fear into the hearts of theoreticians, they point out that much more accurate experiments are possible using two-photon absorption in the 1s–2s transition, and two-photon absorption from a GaAs diode laser, whose second harmonic is locked to the dye-laser frequency, driving a 2s–4s transition. Given the lifetimes of the various participating levels, they feel the ultimate accuracy of such proposed optical experiments could exceed recent high-precision radiofrequency measurements of the 2s Lamb shift, and even that of present day theory of the Lamb shifts.

These elegant experiments of Hänsch and coworkers emphasise the part that the tunable laser has played and will play in precision spectroscopy, a role that it has only recently assumed yet which has already produced a qualitative change in the direction of atomic physics. □

Heat flow on different scales

from Peter J. Smith

UP to the late 1960s, heat flow studies were generally regarded as interesting and potentially important but of little immediate use. Their underlying importance was acknowledged because heat plays a part in almost every conceivable terrestrial process, but the promise they held out to illuminate the nature of such processes was difficult to realise. Part of the problem was that data coverage was poor and there were large areas of the world ith few or no