bees to associate a floral scent with sugar reward (*11*). If this deficit is prolonged by chronic exposure, impacts on colony function will accumulate. As expected for these brain deficits, exposed bumblebees demonstrate reduced foraging ability (*12*) and poor colony growth if exposure continues for weeks (*3, 8, 9, 12*).

Neonicotinoids are not identical in their effects. Each compound activates different, but overlapping, neuronal populations (*9*) and differentially affects learning (*11*), preference-seeking for a particular compound type (*10*), and cross-sensitization, in which heightened responses and toxicity resulting from exposure to one compound extend to related compounds (*9*). Therefore, the effects of the multiple neonicotinoids found to coexist in honey by Mitchell *et al.* may be additive (if they operate on the same receptor types) or different (if they act on different receptor types). Within an intensive agricultural system that is already depleted of natural forage opportunities, chronic bee brain dysfunction due to neonicotinoid exposure would be expected to decrease bee foraging performance further. The resulting lack of incoming forage may then limit bee fecundity.

Mitchell *et al.*'s study highlights two key knowledge gaps: the risks from chronic exposure to individual neonicotinoids, and possible cocktail effects when multiple neonicotinoids coexist. A major scientific challenge is that hundreds of agrochemicals are available to mix on site or use independently on adjacent farms. Although this potential complexity appears to create a scientific impasse, Mitchell *et al.*'s study draws attention to two important untapped opportunities (*4*), namely to monitor honey contamination as an indicator of local habitat contamination and to gather data on actual local pesticide application rates.

Although recording pesticide use is required in the EU (EC no. 1107/2009) and the United States (1990 Farm Bill), it is not collated into a searchable database that might allow correlation of pesticide use with human disease (such as incidence of chronic idiopathic diseases) or ecosystem damage (insect abundance and diversity) (*13*). Systematic collection of these data could provide the statistical power lacking from existing field studies, allowing identification of possible cocktail effects that may then be confirmed in laboratory studies to demonstrate cause-and-effect relationships. ■

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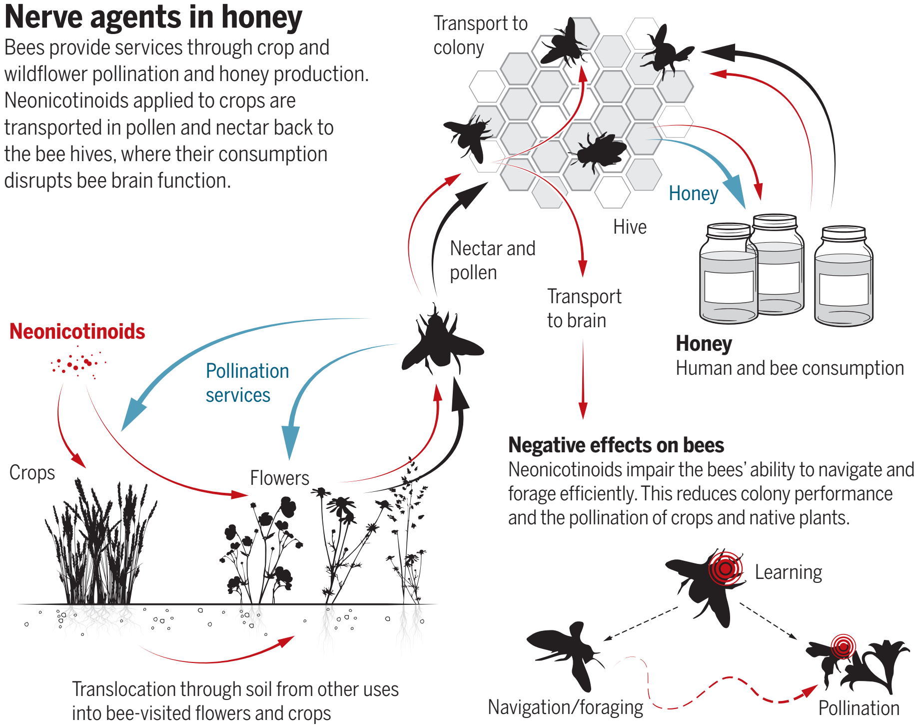
Nerve agents in honey

Bees provide services through crop and wildflower pollination and honey production. Neonicotinoids applied to crops are transported in pollen and nectar back to the bee hives, where their consumption disrupts bee brain function.



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PHYSICS

The proton radius revisited

Hydrogen spectroscopy brings a surprise in the search for a solution to a long-standing puzzle

By **Wim Vassen**

The nucleus of all atoms consists of protons and neutrons, and the simplest of all atoms, hydrogen, has just one proton. The radius of the proton is very small, about 1 fm (1 fm is 10^{-15} m), smaller than the radius of a hydrogen atom by a factor of 60,000. As a proton is such a fundamental particle, much effort is devoted to measuring its size. Since 2010, proton size has been puzzling theorists and experimentalists alike. Measuring transition frequencies in an exotic form of hydrogen, where instead of an electron a muon—an elementary particle 200 times heavier than the electron—is orbiting the proton, a 4% smaller proton size was found (*1*). The near-6σ discrepancy with both regular hydrogen spectroscopy and results from electron-proton scattering was coined the "proton-size puzzle" and finding a solution initiated intense scientific debate, so far without a definite outcome (*2*). On page 79 of this issue, Beyer *et al.* (*3*) present a measurement of the 2S-4P transition frequency in regular hydrogen, one of the lines of the Balmer series. The value of the proton size they deduce from their spectra agrees with the value from muonic hydrogen spectroscopy and disagrees with most previous measurements in regular hydrogen—and there were many. They also find a value for one of the most accurately determined constants of nature, the Rydberg constant, which disagrees with the literature value by more than three standard deviations.

The efforts of Beyer *et al.* were a tour-de-force toward reaching the required accuracy. In the experiment, the frequency of the blue Balmer-β line—a line with an inherent linewidth of more than 10 MHz—was mea-

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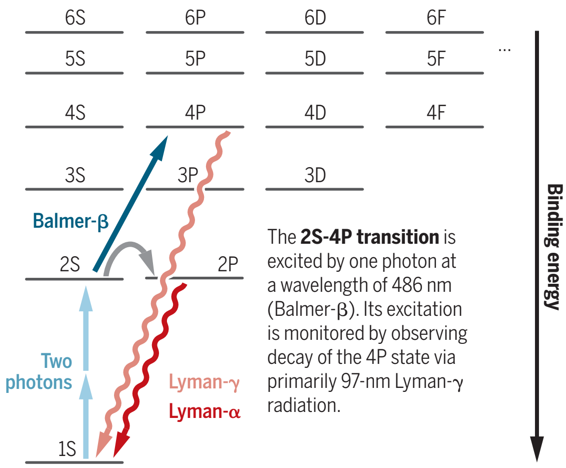
Proton size from hydrogen spectroscopy

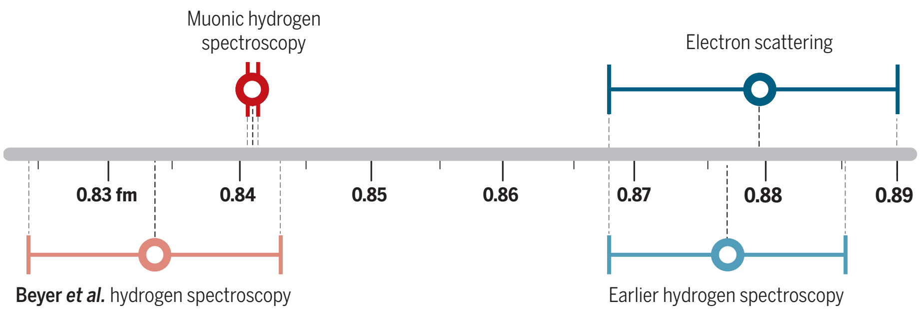
Tiny shifts of level energies occur when an electron spends some of its time inside the nucleus, providing a handle on the proton radius r_p. The shift is largest for low S states. To measure r_p accurately, two transition frequencies are compared.



The **1S-2S transition** is excited by two photons at 243 nm. Its excitation is monitored by observing 121.6-nm Lyman-α radiation from the 2P state, populated from the 2S state in an electric field.

Discrepancies

The proton radius (1 fm = 10^{-15} m) is measured by various techniques. The Beyer *et al.* value agrees with the more accurate result from muonic hydrogen spectroscopy and not with electron-proton scattering data and earlier laser spectroscopy in regular hydrogen.



sured with an accuracy of just a few kHz. This means they had to resolve the line center with an accuracy 1/10,000 the width of the line. To achieve this, they had to understand possible line-shifting mechanisms with that accuracy.

Two frequencies are needed to accurately determine both the proton radius r_p and the Rydberg constant R_∞, relying on the highly accurate quantum electrodynamics (QED) theory of the hydrogen atom. One of these is the frequency of the 1S-2S transition. This transition is extremely narrow because of the small linewidth of the 2S state (1.3 Hz), and its frequency was measured with a tantalizing 10-Hz accuracy in the lab of the authors some years ago (*4*). All other transitions one can use are inherently broad, with linewidths of several MHz. As a second transition, Beyer *et al.* chose the 2S-4P Balmer-β line, which has a 12.9-MHz natural linewidth (see the figure).

In the experiment, a cryogenic beam of atoms in only one of the two 2S hyperfine states was produced by two-photon excitation of 1S ground-state atoms. The 2S atoms were subsequently excited to both the $4P_{1/2}$ and $4P_{3/2}$ fine structure states using a single blue photon. Much effort was put into exciting the atoms at an angle of 90°, as the tiniest deviation of the angle between the atomic and laser beams would shift the line center by the Doppler effect. It is this first-order Doppler effect that determines the final accuracy of the experimental measurement.

Another crucial effect that Beyer *et al.* had to cope with is quantum interference between the neighboring resonances (*5*). Even though both 4P fine structure states are separated by more than 100 natural linewidths, it was found, and studied thoroughly, that tiny shifts of the line center of each occur as a result of the presence of the other. This apparent shift amounts to tens of kHz, to be compared with a much smaller 8.9-kHz shift, which is the proton-radius discrepancy they wanted to resolve. After a thorough analysis, the 2S-4P transition frequency was determined with 2.3-kHz accuracy. The extracted proton size, r_p = 0.8335(95) fm, is more accurate than that obtained from all previous regular hydrogen spectroscopy. The accuracy is as good as the combined accuracy of all these other measurements.

> ***"...the muonic and electronic deuterium data now also seem to be reconciled."***

Beyer *et al.* do not claim to have solved the proton-size puzzle. After all, it is only one measurement, and the data analysis was very complicated. Moreover, one would need to understand why other measurements in hydrogen are so far off or, possibly, exhibit a systematic shift in the same direction. There is presently no explanation for that. Also, the proton size deduced from electron-proton scattering disagrees. Thus, more measurements are what is needed. Several experiments in hydrogen spectroscopy as well as on electron-proton and muon-proton scattering are on the way (*2*). Experiments with heavier nuclei may also shed light on the puzzle. In recent experiments with muonic deuterium, the hydrogen isotope with one proton and one neutron in its nucleus, a smaller deuteron size compared to that of normal deuterium was found using spectroscopy (*6*), reinforcing the original puzzle. Interestingly, with the shifted Rydberg constant as determined by Beyer *et al.*, the muonic and electronic deuterium data now also seem to be reconciled. Spectroscopy on muonic ^{4}He and ^{3}He ions was recently performed and will soon, when theory is finalized, provide the size of the α particle (the ^{4}He nucleus) and the helion (the ^{3}He nucleus), which will then be compared with spectroscopy on ^{4}He and ^{3}He atoms (*7*) and ions (*8, 9*). QED theory for molecules like H_2^+, HD^+, D_2^+ (*10*), and H_2 (*11*) has recently become so accurate that the radii of the nuclei that constitute these molecules can be extracted from precision spectroscopy as well (*12*), thereby allowing yet another means to determine nuclear sizes. ■

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The proton radius revisited

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