The Yin and Yang of Hydrogen

Daniel Kleppner

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REFERENCE FRAME

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"To understand hydrogen is to understand all of physics!" an exuberant colleague once exclaimed, crediting the aphorism to Victor Weisskopf. I asked Viki, but he denied having coined it. Then, after a pause, he added, "But I wish I had." Most physicists understand Viki's sentiment for most physicists are reductionists who aim to understand nature in the simplest possible terms, and hydrogen is a reductionist's dream. For me, hydrogen holds an almost mystical attraction, possibly because I am among the small band of physicists who actually confront it more or less daily.

As an object of obsession, one could do worse than hydrogen. In its special role as the simplest of all atoms, hydrogen has starred in some great episodes in the history of science. Much of what we know about the universe has come from looking at hydrogen, and it cannot be denied that the universe itself is made almost entirely of hydrogen—at any rate, most of the universe that we can see. We might also note hydrogen's technological triumphs, which range from balloons to atomic clocks. One could call hydrogen an atom for all seasons. But the seasons include fall and winter as well as spring and summer, and hydrogen, too, has its dark side as well as its light side. In the timeless metaphor of the Chinese book of wisdom and philosophy known as the *I Ching*, hydrogen has its yin and hydrogen has its yang.

The concept of yin and yang celebrates the complementary nature of things: passive and active, earthbound and airborne, shadowy and luminous. Yin encompasses heavy, dark and earthborne qualities; yang encompasses light, luminous and ascendant qualities. Yin are the lakes, yang are the clouds. Together, yin and yang embody the principle of perpetual change and interchange. By reconciling opposites and extolling flux, the twin concept yin and yang provides a framework for viewing society, history, nature and life itself.

My colleague Thomas J. Greytak and I learned much about hydrogen's yin and yang during our search to see it undergo Bose–Einstein condensation. We set out in that search, full of hope. Others also set out, and they, too, were full of hope. The search took much longer than any of us expected, more than 20 years, long enough to constitute a new chapter in the history of hydrogen. Knowing something of that history was good for the spirit when progress was slow.

The history of hydrogen unfolds in a world of yang, for hydrogen is the lightest of all gases and so luminous that the whole universe is suffused in its radiation. A good starting point is June 1783, when Charles Blagden, assistant to Henry Cavendish, visited Antoine-Laurent Lavoisier in Paris to describe how Cavendish had created water by burning "inflammable air." The facts were clear but Cavendish's explanation—dephlogistonization—was not. Lavoisier immediately repeated the experiment. The consequences were monumental, not because Lavoisier merely confirmed Cavendish's work but because the experiment inspired him to create the concept of a chemical reaction. "Inflammable air" and oxygen join to form water. The very next day, 24 June 1783, Lavoisier reported his results to the Royal Academy of Sciences. The name of hydrogen was born in that event, and so was modern chemistry.

June 1783 was a month of excitement for Paris. The reason, however, was not Lavoisier's discovery—like most important discoveries it was unremarked at the time—but because on 5 June the Montgolfier brothers had flown the first balloon. They filled their balloon with smoke and it floated away on a short flight that caused an absolute sensation throughout France. As to the reason why the balloon floated, however, there was confusion. The Montgolfiers' rationale for filling the balloon with smoke was merely that smoke was the most cloudlike vapor one could obtain.

Jacques-Alexandre-César Charles understood buoyancy, and after Lavoisier's report to the Royal Academy, hydrogen was, so to speak, in the air. Charles immediately set about constructing a hydrogen-filled balloon, raising a public subscription to pay the costs. On 27 August the balloon lifted from the Champs de Mars and ascended a thousand meters. So, barely two months after the news of hydrogen had been announced, it was put to practical use. Possibly this was the quickest case of spin-off from basic research in the history of science. In any case, in the 18th century, just as today, there was no better way to earn society's appreciation than by simply entertaining it.

Hydrogen's buoyant and ascendant nature has been evident ever since Charles's triumphant balloon flight. The optical spectrum of hydrogen first displayed itself imprinted on sunlight. In 1817, Joseph Fraunhofer discovered absorption lines in the sun's spectrum, and 50 years later the Swedish spectroscopist A. J. Ångström showed that Fraunhofer's C and F lines were due to hydrogen. In 1885, J. J. Balmer used Ångström's data to derive the empirical formula that provided the linchpin for Niels Bohr's 1913 paper on the structure of hydrogen. Bohr triggered the search for a new mechanics. Fifteen years later that search culminated in the work of P. A. M. Dirac. Once again hydrogen played a starring role, for the hydrogen spectrum provided the critical test of the Dirac theory. Two decades later, the spectroscopy of hydrogen was extended into the microwave regime by magnetic resonance techniques, and its precision was increased many-fold. The first microwave measurements of hydrogen's hyperfine and fine structure revealed that things were amiss with the Dirac theory. That dilemma was resolved by the creation of relativistic quantum electrodynamics, now the paradigm of field theories, the most precise and precisely tested theory in all of physics.

Hydrogen seems almost aware of its illustrious history for the atom behaves in a regal fashion. Just as monarchs

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DANIEL KLEPPNER *is the Lester Wolfe Professor of Physics and associate director of the Research Laboratory of Electronics at the Massachusetts Institute of Technology.*

never travel unescorted, hydrogen atoms never arrive alone: If you order a tank of hydrogen, what you get is a tank not of atoms, but of molecules. Every research group has its own favored technique for breaking the molecules apart, usually with an electric discharge. If you have seen a hydrogen discharge, you will have been struck by its exuberantly rich and unmistakably royal magenta glow.

This history of hydrogen has been told as a tale of yang, but there is no yang without yin, and hydrogen has secretive as well as exuberant properties. At the very center of the atom dwells the almost but not totally pointlike proton. At an advanced level of precision, that little knot of hadronic mischief mocks hydrogen's perfection. The proton's finite size shifts the energy of hydrogen only by about one part in 10^9, but the precision of today's measurements has reached a few parts in 10^{13}. Ignorance about the proton is balking comparison of the most precise experiment in all of physics—spectroscopy of hydrogen's 1S–2S transition frequency—with the most precise theory in all of physics. The lesson from this conundrum is that understanding hydrogen requires understanding the proton's inner world of quarks and gluons. Such an unfolding of inner worlds can be viewed either as the glory or the despair of the reductionist vision. One might paraphrase the aphorism as, "To understand hydrogen, one must understand all of physics."

On a more prosaic level, hydrogen has what might be charitably described as some minor character defects. Experimentally, the atom behaves more like a prima donna than a member of royalty. Hydrogen can be impossible to find when you want it. Alkali metal atoms, in contrast, conveniently signal their presence by spontaneously ionizing if they hit a hot tungsten filament, or fluorescing brilliantly under laser excitation. Neither strategy works with hydrogen. Hydrogen demands a bravura laser system if it is to be excited optically, for its principal transition—the Lyman-alpha line—lies at a wavelength beyond the reach of today's lasers. And practically every experimenter who produces the atom using an electrical discharge source has experienced the sinking sensation that occurs when the discharge goes into a temperamental funk, its magenta color replaced by watery blue light. The atom flow falters and the experiment must be halted until the discharge can be coaxed back into operation. By then, so much time has passed that the experimental run probably needs to be started over from scratch.

Notwithstanding these defects, hydrogen continues to hold a special attraction for physicists. Undoubtedly this is one of the reasons that my colleagues and I became swept up in the search for Bose–Einstein condensation (BEC) of an atomic gas. The search employed hydrogen because the atom has a remarkable property: If its electron spin is polarized so as to prevent the formation of molecules, the gas is the most noble gas of all—even more inert than helium. Helium liquefies at a temperature of 4.2 K. Spin-polarized hydrogen never liquefies: It remains a gas at temperatures down to absolute zero.

When the search for BEC started, hydrogen seemed almost perfectly suited to the task. There was no mystery about the required temperature and density: The condensation takes place when the atom's de Broglie wavelength is approximately the distance between atoms. Because of hydrogen's low mass and correspondingly long de Broglie wavelength, for a given density the transition would occur at a much higher temperature than for any other atom. Another advantage was atomic hydrogen's close to ideal behavior: its collision cross section is so small that finite size effects can be reliably calculated. Finally, it seemed possible that hydrogen could be cooled to subkelvin temperatures merely by letting the gas make contact with a liquid helium surface. Of all atoms, only hydrogen could be cooled this way, for only hydrogen interacts so weakly with helium that it would remain in the gas phase at temperatures down to roughly 0.1 K.

All these yang-like features of hydrogen attracted us to the search for BEC. That was in 1977. Inspired by hydrogen's yang, we ran into hydrogen's yin. To jump forward to 1995, the discovery of BEC in atomic gases is now a well-known story, the most exciting single development in atomic physics since the invention of the laser. The condensates, however, were composed not of hydrogen but of alkali metal atoms. As far as BEC is concerned, hydrogen's glamorous attractions proved to be mostly an illusion. Although hydrogen could indeed be cooled to cryogenic temperatures, it turned out that alkali metal atoms could be cooled to much lower temperatures by laser cooling techniques. At such temperatures, these commonplace atoms should rightfully be in a useless solid phase. However, when they are isolated in a trap, they remain in the gas phase. (The reason is this: The first step in the gas-to-solid transition is for two atoms to form a molecule. However, because atoms collide elastically, molecular formation requires that three atoms collide simultaneously. At the densities for BEC, such three-body collisions are so rare that the system lives on as a metastable gas.) The final stage of cooling employs forced evaporation. In this process, hydrogen's small cross section is not a virtue but an almost fatal vice. Evaporative cooling needs collisions to maintain thermal equilibrium by redistributing the energy after the most energetic atoms escape from the system. Unfortunately, the cross section for hydrogen is more than a thousand times smaller than for the alkali metal atoms. Alkali metal atoms practically rush to low temperatures; hydrogen must be reluctantly coaxed.

In spite of hydrogen's shortcomings, we pressed on toward BEC even after condensation was achieved in the alkali metal atoms. If BEC could be achieved with hydrogen, the conditions would be different from those in all other experiments, and in any case hydrogen continued to possess its special attraction. Nevertheless, with a now aged and unreliable apparatus that was relentlessly breaking down, and little assurance that condensation could be achieved, it took considerable faith for our students to stick with the search.

Late one night last June, a phone call from the lab implored me to come quickly. I had a pretty good idea of what was up because BEC in hydrogen had seemed imminent for more than a week. As I drove in the deep night down Belmont Hill toward Cambridge, still dopey with sleep, the blackness of the sky suddenly gave way to a golden glow. I was not surprised because I had a premonition that the heavens would glow when BEC first occurred in hydrogen. Abruptly, streamers of Bose–Einstein condensates shot across the sky, shining with the deep red of rubidium and brilliant yellow of sodium. Small balls of lithium condensates flared and imploded with a brilliant red pop. Stripes of interference fringes criss-crossed the zenith; vortices grew and disappeared; blimp-shaped condensates drifted by, swaying in enormous arabesques. The spectacle was exhilarating but totally baffling until I realized what was happening: The first Bose–Einstein condensates were welcoming hydrogen into the family! For hydrogen, I thought, this was truly a night of yin, a night of yang.

I thank Kerson Huang for introducing me to the I Ching. *A more quantitative description of BEC in hydrogen is reported in Thomas Killian* et al., Physical Review Letters, *volume 81 (1998), page 3807 and Dale Fried* et al., Physical Review Letters, *volume 81 (1998), page 3811.* ■