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MASAKI HORI

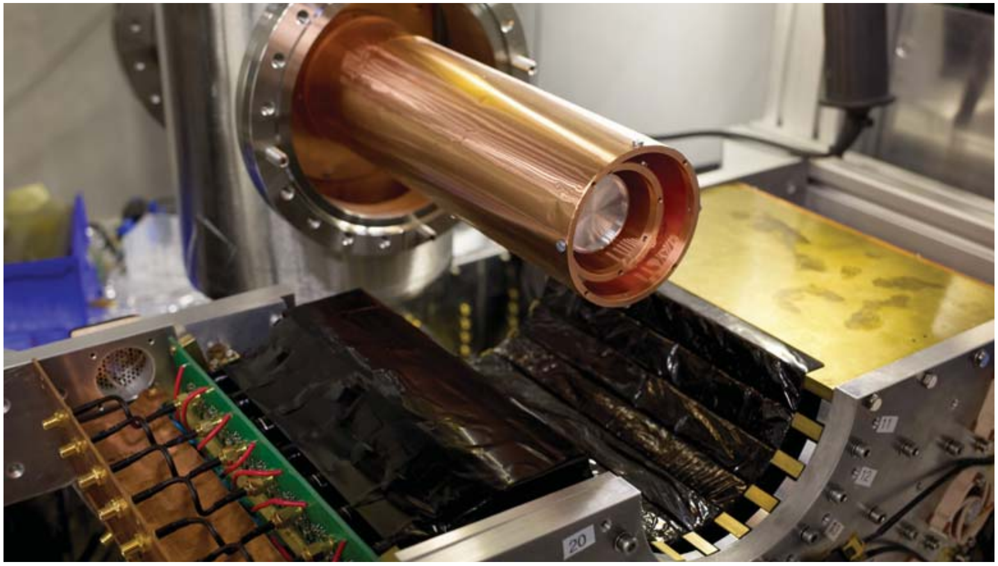

FIGURE 1. PION PHYSICS IN A TUBE. In this disassembled experiment, a 4.2-cm-diameter aluminum cylinder, just visible inside the copper radiation shields, is a vessel for holding superfluid helium. When a pion beam streams through the cylinder, some of the pions displace atomic electrons to create pionic helium atoms. A suitably tuned laser beam passing through the cylinder in the opposite direction excites some of the pionic atoms into short-lived states in which the pion and nucleus promptly and destructively collide. The fission products of the annihilated atoms, detected with an array of plastic scintillators surrounding the cylinder (half of them shown here), indicate that the laser was on resonance with an atomic transition.

The best atomic clocks, which mark time by measuring the frequency of an atomic resonance, operate with an uncertainty of around 10^{-18}. If left to run for the age of the universe, they'd lose less than a single second. That astonishing precision is made possible by laser spectroscopy.

The quantum mechanical laws that give rise to atomic structure aren't limited to protons, neutrons, and electrons. One can, in principle, construct a hydrogen-like atom out of any two particles of opposite charge, or replace any electron in a larger atom with any other negatively charged particle. Laser spectroscopy on those exotic atoms can probe the properties of both the unusual particles and the ordinary ones.

In particular, by studying the spectrum of antihydrogen, researchers can search for differences between matter and antimatter (see PHYSICS TODAY, February 2017, page 16). And muonic hydrogen, in which a muon replaces the electron, has been used to measure the charge radius of the proton: The muon, 200 times more massive than the electron, occupies a smaller atomic orbital that's more sensitive to the proton's nonzero size.

Now Masaki Hori of the Max Planck Institute of Quantum Optics and his colleagues have made the first laser spectroscopic measurement on an atom containing a meson.[1] Specifically, they've studied pionic helium, in which one of the electrons in an ordinary helium atom is replaced by a negatively charged pion. With a lifetime of just 26 ns, the charged pion is the shortest-lived particle ever to be probed by exotic-atom laser spectroscopy.

Because an atom's spectroscopic resonances depend on the masses of its constituent particles, Hori and colleagues' technique could eventually lead to an improved measurement of the charged pion's mass, currently known to a fractional precision of 10^{-6}. In turn, through kinematic analysis of the charged pion's main decay channel—which yields a muon and a muon antineutrino—the pion mass measurement could provide a much-needed additional constraint on the neutrino mass.

Exotic atoms

The pion's short lifetime poses an experimental challenge. Positrons and antiprotons, the components of antihydrogen and numerous other exotic atoms, live effectively forever—as long as they're kept away from their antiparticles—so there's no limit on how long they can be cooled, trapped, or shuttled around with electric and magnetic fields. Even the muon, with a lifetime of 2 μs, survives long enough to be decelerated and inserted into an atom.

The pion allows no such leeway. There's no time to do anything more sophisticated than take the pions straight off a beamline, smash them into a target element of interest, and hope that some of them displace atomic electrons to form pionic atoms.

Unfortunately, the resulting atoms have even shorter lifetimes than the pions they contain. Isolated charged pions decay through the weak interaction. But if a pion comes across an atomic nucleus, it reacts with one of the nucleons through the much faster strong interaction, destroying both the nucleus and the pion.

Typically, a pion enters an atom in an orbital of high principal quantum number n, then immediately tumbles into a lower-energy orbital, emitting photons and casting electrons out of the atom as it goes. It makes its way to an orbital that has large overlap with the nucleus, then blows it to bits. The whole process, which takes a few picoseconds or less, has been well studied. Indeed, it's from the energies of the photons emitted from pionic nitrogen that we know the pion mass as well as we do.[2] But the short-lived atoms can't be studied with the accuracy of laser spectroscopy.

Helium promised an exception. If a

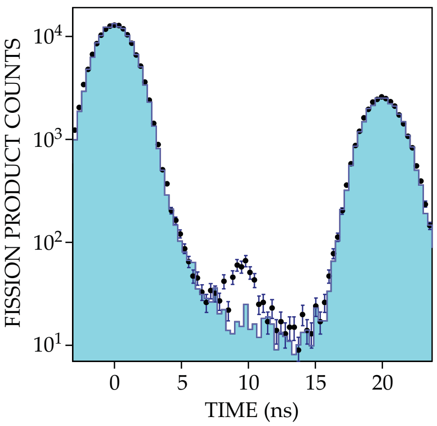

FIGURE 2. MOST PIONIC HELIUM ATOMS self-destruct immediately, even without laser excitation. So when pions arrive in bunches spaced by 20 ns, their resulting fission products are likewise detected in bunches, as shown by the blue histogram of data taken with the laser switched off. The only way to see a spectroscopic signal from the few longer-lived pionic atoms is to time the laser pulses to arrive between the pion bunches. The black data points show a successful spectroscopic detection with the laser tuned to 1631.4 nm. (Adapted from ref. 1.)

pion enters a helium atom in an orbital of high angular-momentum quantum number l (say, $n = 16$, $l = 15$), it's left with nowhere to go. It can't move to another orbital without a large change in angular momentum, and the remaining atomic election in a tightly bound, zero-l orbital can't do much to compensate. Because the high-l orbital has little overlap with the nucleus, the pionic helium atom could live for almost as long as the pion itself. With the right tools and techniques, that's long enough to probe with a laser.

Finding the resonance

Hori and colleagues booked time at the most powerful pion beamline in the world, at the Paul Scherrer Institute (PSI) in Switzerland. Protons from the PSI ring accelerator collide with a chunk of graphite to create a stream of charged pions for user experiments. (The J-PARC accelerator in Japan creates pions the same way; see Physics Today, June 2020, page 14.)

The experimental apparatus for making and detecting pionic helium is shown in figure 1. To hold the liquid helium for their target, the researchers needed a vessel with walls sturdy enough to contain the cryogenic fluid but thin enough for the pions to pass right through. They chose a tube-shaped container made of aluminum with walls 0.5 mm thick. "It took a year of failed prototypes, as the thin walls kept buckling," says Hori, "but we finally got a chamber that didn't leak or deform at cryogenic temperature."

None of the pionic helium atoms ever leave the liquid helium environment. Almost all of them are destroyed through the energetic collision of the pion and the nucleus that sends nucleons flying in random directions. The nucleons, like the pions, pass right through the thin aluminum walls, and they're detected by an array of plastic scintillators surrounding the helium target.

Some 98% of pionic helium atoms form in low-l states that decay almost instantaneously; the remaining 2% occupy high-l states that meet a more leisurely demise over the ensuing tens of nanoseconds. If those rare remaining atoms could be excited by a laser pulse into a lower-l state, they'd be prompted to undergo fission all at once. Their decays would show up as a blip in the scintillator trace that's present when the laser is on and absent when it's off—a telltale sign that the laser is tuned in to an atomic resonance.

The timing needed to be precise. The PSI accelerator generates protons, and thus pions, at 50 MHz, or in bunches 20 ns apart. "Essentially, the experiment is temporarily blinded every 20 ns by the arrival of new particles," explains Hori. "That time window seemed too short for spectroscopy. I asked if they could increase the spacing, but it would have been too much of a disturbance for the other experiments at the facility."

Ultimately, the experimenters took the risk and proceeded anyway. To know where to focus their spectroscopic search, they enlisted the help of theorist Vladimir Korobov of the Joint Institute for Nuclear Research in Dubna, Russia, to calculate the expected transition energies of pionic helium. At first, they sought to excite transitions from the $n = 16$, $l = 15$ state, the high-l state expected to be most populated. But despite months of work, they found nothing.

Running out of beam time and grant money, they tried exciting a transition from the $n = 17$, $l = 16$ state. Within days, they saw a signal, shown in figure 2 as the difference between the black data points (collected with the laser on) and the blue histogram (laser off). The signal peak nestled between two much larger peaks, created by the short-lived states, so it was visible only when the data were plotted logarithmically.

But there was a problem: The resonance wasn't quite where it was supposed to be. Korobov had calculated that it should be centered on a frequency of 183 681 GHz (equivalent to a wavelength of 1632.1 nm), and the laser frequency that generated the signal was 0.04% higher than that. The difference is far too great to be explained by uncertainty in the pion mass. Instead, the researchers attribute it to atomic collisions in the liquid helium that distort the pionic atoms' orbitals and shift their energies. The same mechanism may explain why they didn't see any signal from the $n = 16$, $l = 15$ state—collisions may distort some atomic states so much as to render them effectively unbound. Says Hori, "This is a far more fragile system than any other exotic atom, or even any normal atom, that's been studied with laser spectroscopy before."

To get a handle on the collision effect, Hori and colleagues plan to swap out the liquid helium target for a gaseous one whose density they can adjust. A more dilute gas means fewer atomic collisions. By measuring the resonance in gases of different density and extrapolating to zero, they should be left with the resonant frequency of an isolated pionic helium atom. From there, they'll be able to calculate the pion mass. If they encounter no measurement limitations other than the resonance's natural linewidth, Hori estimates that they could reach a fractional uncertainty as low as 10^{-8}.

Neutrinos and more

An improved measurement of the pion's mass will make possible a more precise analysis of its decay into a muon and muon antineutrino. Solving the kinematic equations for the neutrino's mass gives an expression that depends on the square of the charged pion mass. (It also depends on the square of the muon mass, but that's much better known.) So although the pion mass is known to within 240 eV, the best that can be said of the muon neutrino from pion decay is that its mass is less than 190 keV. By pinning down the pion mass by an additional two orders of magnitude, laser spectroscopy could help to refine that limit.

With the help of theory, one can arrive at a far tighter constraint. Current understanding of neutrino physics holds that all three known flavors of neutrino—electron, muon, and tau—are mixtures of the same three mass states. The mixing allows neutrinos to transform from one flavor into another, and studies of that flavor oscillation, which measure the differences between the squares of the masses, show that all three masses are within tens of meV of one another. Furthermore, the KATRIN (Karlsruhe Tritium Neutrino) experiment, a study of nuclear beta decay, found[3] that the electron antineutrinos emitted in that process can't be more massive than 1.1 eV.

That line of reasoning implies that the muon neutrino mass is also in the neighborhood of 1 eV or less, and certainly not as large as 190 keV. But neutrino mass is a mysterious thing. It's not part of the standard model of particle physics, and there may yet be theoretical surprises in store. Experiments that directly probe each neutrino flavor's mass may still be valuable.

Now that pions can be inserted into atoms and manipulated with lasers, Hori hopes that laser spectroscopy will prove to be a more general technique for studying other mesons. In addition to the negatively charged pion—a bound state of a down quark and an up antiquark—another appealing target is the negatively charged kaon, which replaces the down quark with a strange quark. The kaon's lifetime, at 12 ns, is slightly less than half as long as the pion's. And its mass, with a fractional uncertainty of more than 10^{-5}, is in need of a more precise measurement.

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Cold, supersaturated urban air could be accelerating pollutant particle growth

A new experiment suggests that ammonium nitrate particles nucleate and quickly grow in winter conditions.

In early April, city dwellers of India's northern provinces experienced once-in-a-lifetime views of the snow-capped Himalayas, thanks to a rare absence of smog. The foggy mixture of particles and gases will certainly reappear in the region once coronavirus restrictions are lifted and the air pollution returns. Particulate matter in the atmosphere is a leading cause of lung disease and may contribute to neurological diseases such as Alzheimer's. A better understanding of the pollutants that lead to smog formation is necessary for any mitigation effort to succeed.

FIGURE 1. SMOG LOOMS OVER PRAGUE on a February day. The pollutant, which forms when particulate matter reacts with UV radiation in the atmosphere, is a major contributor to respiratory disease. Still, it's unclear how the large particles found in smog can grow in urban air. (Courtesy of Vojife/Wikimedia Commons, CC BY 3.0.)

Some particles in the atmosphere, called primary particles, form directly from combustion or mechanical generation. Other particles, called secondary particles, form from trace gases that condense and stick to the surfaces of existing particles, and sometimes undergo complex chemical evolution. Winter smog, shown in figure 1, is a mixture of both types of particles. Rapid growth is essential to the survival of secondary particles, but how they can grow so quickly in polluted urban air is a puzzle. Observations suggest that in urban air, vapors and particles are almost in equi-