

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, found³ 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.

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



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.)

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-

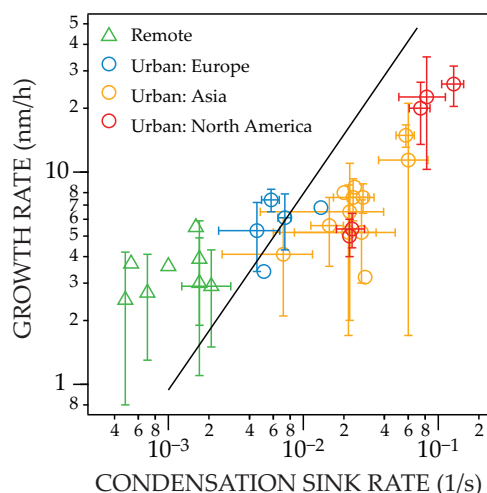


FIGURE 2. ATMOSPHERIC PARTICLE GROWTH RATES, shown here on the vertical axis, are only modestly faster in many urban environments (red, orange, and blue dots) than in remote ones (green triangles). The condensation sink rate (horizontal axis) describes how quickly newly formed clusters are scavenged by existing particles and is higher in urban environments than in remote ones. The persistence of those clusters depends on the ratio of the condensation sink and growth rates (the slope of the black line corresponds to a constant ratio), with small urban particles likely to be lost by scavenging unless they grow quickly. (Adapted from ref. 1.)

librium, so particles only grow slowly.

Now Neil Donahue of Carnegie Mellon University and colleagues have shown in a laboratory experiment that common nitrogen-containing vehicle emissions may accelerate the particle-formation process.¹ Those compounds have previously been thought to exist in concentrations near their equilibrium values in the atmosphere and therefore not to play a role in particle formation or early growth. The researchers identified conditions under which the vapor pres-

ures of precursor pollutants in cold temperatures, typical in some winter months and in the upper atmosphere, allow nitric acid and ammonia to condense and quickly grow into large secondary particles of ammonium nitrate. Those particles can add significantly to the total number of particles in the atmosphere and contribute to the associated health effects.

Growing pains

Internal combustion engines, incinerators, cooking fires, and other sites of combustion in cities lead to high atmospheric concentrations of gas-phase pollutants, many of which readily condense into tiny clusters of molecules a few nanometers in size. But it's not easy for a small cluster of molecules to grow enough to form a larger stable particle,

typically characterized as a cluster 10 nm or larger.

Many nascent clusters simply evaporate due to an effect identified in 1871 by Lord Kelvin: Smaller clusters have greater curvatures than larger ones, and therefore tend to have higher surface vapor pressures. As a result, smaller clusters evaporate more readily. For molecular clusters with diameters less than about 10 nm, molecules are more likely to escape than remain stuck together.

Other newly formed clusters are scavenged by existing particles. As tiny clusters grow, they reach a size where they can get caught in the turbulent wake of a larger, existing particle and stick to its surface. As a result, the total number of particles does not increase. The scavenging of new clusters by existing particles is known as the condensation sink rate.

The ability of small, newly formed clusters to grow into larger, stable particles depends on the ratio of the condensation sink and the cluster growth rate. Observations from Europe, North America, and Asia, summarized in figure 2, show that particle growth rates in urban areas are only a few times greater than growth rates in remote areas, whereas the condensation sink rate in urban areas is up to two orders of magnitude larger. The relatively efficient particle removal rate in urban areas, combined with the relatively slow growth rate of particles (10–20 nm/hr), has led atmospheric researchers to seek a mechanism by which particles can reach a diameter more than 10 nm within seconds to minutes within the rich chemical mixture of urban atmospheres.

Cows, cars, and CLOUD

Ammonia is the most significant base gas in the atmosphere, where it contributes to the formation of ammonium nitrate in the presence of nitric acid. In rural areas, ammonia is closely associated with livestock dung; in urban areas, vehicle catalytic converters may generate a level of ammonia similar to that produced in some agricultural regions.² The



FIGURE 3. THE CLOUD (COSMICS LEAVING OUTDOOR DROPLETS) CHAMBER at CERN is a 26-cubic-meter tank in which temperature and gas concentrations are carefully controlled to simulate natural atmospheric conditions between the ground level and the stratosphere. The proton synchrotron serves as an artificial source of cosmic rays, which simulates natural atmospheric conditions and may stabilize particles that form from the ionized gases in the chamber. External instrumentation allows for constant monitoring of the chamber's contents. (Courtesy of CERN/Neil Donahue.)

most common pathway for the formation of ammonium nitrate in a relatively clean atmosphere keeps the compound near chemical equilibrium with gaseous ammonia and nitric acid. As a result, that mechanism is unlikely to increase the number density of particles unless the atmosphere becomes supersaturated with nitric acid and ammonia.

To investigate what conditions may drive supersaturation and new particle formation in an urban setting, Donahue and his colleagues studied mixtures of common pollutants in the CLOUD (Cosmics Leaving Outdoor Droplets) chamber at CERN (figure 3). The facility—modeled after cloud chambers used in particle physics in the 1950s—provides an environment in which to simulate vapor and particle interactions under conditions representative of the atmosphere from the lower troposphere up to the stratosphere. UV light generated by a built-in fiber-optic system mimics the energy provided by the Sun's cosmic rays. That radiation ultimately controls how molecules ionize at different altitudes.

In a series of experiments designed to replicate winter conditions in polluted cities, the researchers introduced various combinations of nitric acid, ammonia,

sulfuric acid, and their precursor molecules into the CLOUD chamber. They exposed the gases to a range of temperatures typical of the lower atmosphere and varied the radiation input to control ion distribution. Mass spectrometers and particle counters that encircle the chamber determined the resulting concentration of gases and the properties of newly formed particles.

The team found that at temperatures warmer than -15°C , ammonium nitrate and sulfuric acid followed a known pathway to form small clusters of molecules.³ Once clusters of ammonium sulfate reached a threshold size, ammonium nitrate began to condense onto the clusters, resulting in rapid particle growth—above 100 nm/hr—as long as the temperature remained below 5°C . At temperatures colder than -15°C , which can occur in humid air outflows above some clouds, the nitric acid and ammonia gases nucleated through an acid-base stabilization mechanism to form particles of ammonium nitrate, which then grew via additional condensation of ammonium nitrate.

Calculations showed that the critical size at which ammonium nitrate begins rapid growth depends on the maximum

concentrations of the ammonia and nitric acid.⁴ Once that size is reached, rapid growth continues until the precursor vapors return to the chemical equilibrium commonly found between ammonia, nitric acid, and ammonium nitrate.

Large-scale atmospheric transport models do not take into account the newly proposed path to particle formation. The CLOUD experiments suggest that it may be important instead to consider those vapors using dynamic calculations. The researchers propose that variations in temperature and emission sources in cold urban settings provide the conditions necessary for localized supersaturation of nitric acid and ammonia. By imposing regulations to control nitrogen emissions, urban planners could reduce the concentration and growth of particles and improve air quality.

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Chip-scale sensor detects light's orbital angular momentum

The photocurrent in an unusual material could facilitate an increase in the information density of optical communications.

Light often has spin angular momentum, more commonly referred to as left or right circular polarization. Only in the past 30 years have researchers been able to impart orbital angular momentum (OAM; see the article by Miles Padgett, Johannes Courtial, and Les Allen, *PHYSICS TODAY*, May 2004, page 35). Instead of the usual flat wavefront, light with nonzero OAM has a helical wavefront that turns like a corkscrew in the direction of propagation. The quantum number m describes how tight the light's corkscrew motion is. For example, $m=1$ means a full clockwise rotation in a wavelength, and $m=-2$ means two full counterclockwise rotations in a wavelength.

OAM provides additional degrees of

freedom for encoding information in optical communications. Modern optical networks rely on wavelength and intensity modulations to send data; the addition of polarization and OAM could pack in more information without boosting traffic. What's more, unlike polarization, which has two modes, m can take any integer value. Modes of different m are also orthogonal and wouldn't interfere with one another during transmission.

Ordinarily, measuring OAM requires a roomful of bulky optics. But Ritesh Agarwal at the University of Pennsylvania and his colleagues have found a compact way to detect light's OAM through the induced photocurrent in a device that's just tens of micrometers across.¹ Their technique could make it

easier to read out information encoded in the OAM.

Gaining momentum

To measure m , researchers typically interfere light with a reference beam or send it through a hologram or specially designed aperture. The nature of the interference or diffraction pattern manifests the OAM. But those measurements not only require table-scale setups; they are also limited in the number of modes they can measure. For example, most holograms can detect only one particular value of m , so a new one must be swapped in for each mode.

In CCDs and other solid-state sensors, light is detected through its interactions with matter. A material's response depends primarily on the local incident number of photons—that is, the intensity. Phase information is usually lost when intensity is converted to photocurrent. Because a clockwise helical