orbiting an atom such as strontium between energy states.

But a nuclear clock could do even better. It would use the more energetic transition of boosting the nucleus's protons and neutrons to higher energy states. This would use slightly higher frequency radiation, meaning that time could be sliced even more finely to create a more precise clock. More importantly, such a clock would be much more stable than an optical clock, because particles in the nucleus are less sensitive than electrons to external fields or temperature.

But finding a material with a suitable nucleus has proved difficult. Energy transitions in most nuclei tend to be huge, requiring much more than the nudge of a tabletop laser. In the 1970s, physicists discovered that thorium-229 is an anomaly – its first energy state is extremely close to its lowest, ground state. And in 2003, physicists proposed using thorium-229 as the basis of a super-stable clock, but they needed to find the precise energy of the transition and its corresponding laser frequency, which would have been impossible to predict with any accuracy using theory. Since then, experimentalists have used range of methods to narrow down the figures.

To observe the transition, researchers placed radioactive thorium atoms into crystals of calcium fluoride that were a few millimetres wide. Scanning across the expected region with a purpose-built laser, they eventually hit on the right frequency – around 2 petahertz (10^{15} oscillations per second) – which they detected by spotting the photons emitted as the nuclei returned to the lower energy state. Co-author Thorsten Schumm, an atomic physicist at the Vienna University of Technology, recalls scrawling "found it" in large red letters across his lab book at a meeting convened the next day to discuss the promising-looking signal. "It was crystal clear," he says.

The team pinpointed the frequency with a resolution 800 times better that of the next best attempt. A team at the University of California, Los Angeles, has since reproduced the result using a different crystal, but the same frequency, says co-author Ekkehard Peik, a physicist at PTB. It's "a very nice confirmation", he says.

Fundamental physics boost

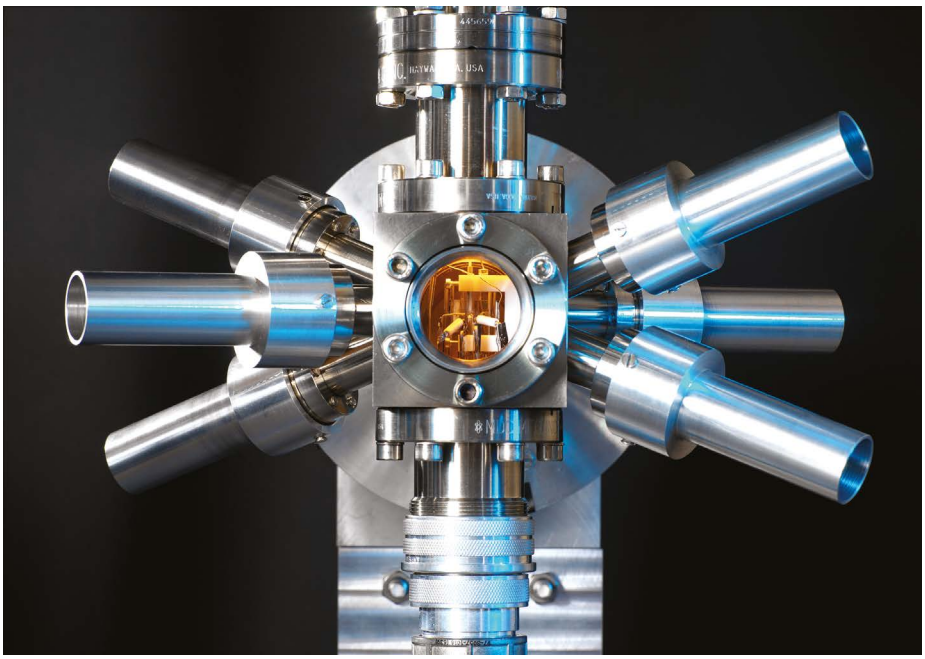
To turn the system into an actual clock, physicists will need to markedly reduce the resolution of the laser, so that it stimulates the nucleus at almost exactly the right frequency to be read off reliably, says Peik. Building such a laser "remains a big challenge, but there are little doubts that it will be achievable in the near future", adds Kocharovskaya.

If all goes well, the team says that a thorium-based nuclear clock could end up being around ten times more accurate than the best optical clocks. Hosting the nuclei in a solid crystal could also help to make the clock more compact and portable than optical systems.

Scientific methods that were made possible by super-precise optical clocks, such as probing Earth's gravitational field by measuring differences in clock speed, "could get a major boost", says Kocharovskaya.

Physics could also benefit at a deeper level. A nuclear clock would be around 10,000 times more sensitive to changes in fundamental constants – such as the strength of the electromagnetic and strong nuclear forces – than an optical clock is, says Fuchs. This means that they could detect proposed forms of dark matter, an invisible substance that physicists think accounts for 85% of material in the Universe, and which are predicted to make minuscule changes in the strength of these forces.

"It could be that there's very 'light' dark matter that wiggles around and that could make these fundamental constants wiggle," says Fuchs. Nuclear clocks might be able to detect that wiggle, she says, because the energy of their transition is governed by these forces, and any change in their strength would alter the clock's tick. Nuclear clocks could also detect whether some particle masses change over time, she adds. Fuchs and her collaborators are already working on their first paper, about the frequency measurement. "This is exciting us quite a lot," she says.



ANDREW BROOKES, NATL PHYSICAL LAB./SPL

Optical clocks (pictured) are currently physicists' most precise timekeepers.

BIRD FLU IN US COWS: WHERE WILL IT END?

Scientists worry that the H5N1 strain of avian influenza will become endemic in cattle.

By Sara Reardon

Concerns that pasteurized milk in the United States is teeming with H5N1 avian influenza virus are over. But there's no sign that the outbreak in cows is over, and scientists are increasingly concerned that cattle will become a permanent reservoir for this adaptable virus – giving it more chances to mutate and jump to humans.

New data show that the virus can hop back and forth between cows and birds, a trait that could allow it to spread across wide geographical regions (see go.nature.com/3qajc9p). Although the virus kills many types of mammal, most infected cows don't develop severe symptoms or die[1], meaning that no one knows

BEN BREWER/REUTERS

Dairy cattle seem to shake off infection with the H5N1 strain of influenza virus.

whether an animal is infected without testing it. Moreover, a single cow can host several types of flu virus, which could, over time, swap genetic material to generate a strain that can more readily infect humans.

"Eventually the wrong combination of gene segments and mutations inevitably comes along," says Michael Worobey, an evolutionary biologist at the University of Arizona in Tucson. "Whatever opportunity we may have had to nip it in the bud we lost by a really slow detection."

Viral expansion

Various forms of H5N1 have been circulating since the 1990s. A particularly deadly variant that was first detected in 1996 has killed millions of birds and has been found in numerous mammalian species. But until now, cows were not among the virus's known hosts.

US officials first announced on 25 March that H5N1 had been found in cattle, and cows from 36 herds in 9 states had tested positive by 7 May. Tests of pasteurized milk have found no living virus. But the virus's increasing ubiquity is making scientists uneasy.

"Every time it gets a new mammalian host species, like cows, there's more risk of human transmission and reduced human immunity," says Jessica Leibler, an environmental epidemiologist at Boston University in Massachusetts.

Bovine breakthrough

Genomic data are shedding light on the origins of the cattle outbreak. In a 1 May preprint[2] posted on bioRxiv, scientists at the US Department of Agriculture analysed more than 200 viral genomes taken from cows and found that the virus jumped from wild birds to cattle in late 2023. That result corroborates findings by Worobey and others in an analysis posted on the discussion forum virological.org on 3 May (see go.nature.com/4baezra). (Neither article has yet been peer reviewed.)

Because cows infected with H5N1 generally don't die of the flu, they are "effective mixing vessels" in which viruses can swap genetic material with other viruses, says Angela Rasmussen, a virologist at the University of Saskatchewan in Saskatoon, Canada. Even worse, the current strain seems to infect several species equally well. "If you have a virus that's hopscotching back and forth between cows, humans and birds, that virus is going to have selective pressures to grow efficiently in all those species," she says.

The larger the number of infected animals, Rasmussen says, the more chances the virus has to acquire mutations, such as the ability to grow in the upper respiratory tract, that could make it more transmissible between people.

Dangerous reservoir

From a human perspective, Worobey says, cows might be one of the worst possible animal reservoirs for influenza because of their sheer number and the degree to which humans interact with them. Culling poultry has curbed previous bird flu outbreaks, but Rasmussen says that isn't a viable option for cattle. The animals are too valuable and, unlike birds, don't seem to die from the infection.

H5N1 could even become endemic in cows, says Gregory Gray, an infectious-disease epidemiologist at the University of Texas Medical Branch at Galveston. Strains related to H5N1 are already endemic in chickens and pigs in some parts of the world.

Researchers aren't sure how the virus is spreading between herds. Wild birds, which congregate around cattle feed and defecate in the cows' water supply, are one probable source. And birds can spread infections much further than cows can and are much less controllable, Gray notes.

Some evidence has suggested that farm equipment, such as milking machines, could be to blame, but several scientists worry that the cause could be airborne. "I'm really thinking that's occurring and we've not been able to study it," Gray says, mainly because farmers have been reluctant to allow inspectors to test their cattle. Some related variants that infect horses have been found to spread through the air for kilometres, which could explain how the current strain has moved between dairy farms.

Until more is known about the virus's transmission route, Worobey says, it's hard to determine the best way to contain it. Since late April, the US Department of Agriculture has required that cows be tested before being transported across state lines. That won't necessarily stop the spread, but it could at least help researchers to understand where the virus is going.

Herd immunity

If the virus is airborne, Gray says, vaccinating cows might be an option. H5N1 vaccines have not yet been used in US cattle. But influenza vaccines have proved effective in pigs and poultry, and researchers are testing them against the H5N1 strain infecting dairy herds.

Data on how well the virus spreads between people are scarce. A study[3] published on 3 May in the *New England Journal of Medicine* confirmed that one dairy worker in Texas had been infected. But the people who worked and live with the infected person have not been tested.

Still, US officials have not reported a large number of deaths or severe cases in humans, suggesting that the virus hasn't become highly transmissible or deadly, Worobey says.

Below the radar

But Gray says that there have been anecdotal reports of many more human cases. Leibler suspects that exposure of farm workers is widespread. "When you see symptomatic patients, that's the tip of the iceberg," she says. In the worst-case scenario, she says, the virus would spread in several species for a long time, accumulating mutations that prime it for causing a pandemic in the future. "We have an awareness now from the COVID pandemic of how devastating that could be," she says.

Leibler hopes that public-health efforts will begin testing workers and their families so that any transmission in humans will quickly be detected. "H5N1 is with us," she says. "It's not a virus that's going to disappear by any means."

1. Burrough, E. R. *et al. Emerg. Infect. Dis.* https://doi.org/10.3201/eid3007.240508 (2024).
2. Nguyen, T.-Q. *et al.* Preprint at bioRxiv https://doi.org/10.1101/2024.05.01.591751 (2024).
3. Uyeki, T. M. *et al. N. Engl. J. Med.* https://doi.org/10.1056/NEJMc2405371 (2024).