colleagues' analysis of the fossil specimen stands out is in their use of wide-ranging digital reconstruction that corrects distortions of the fossil's shape, and estimates missing parts. These digital methods are readily available and offer unique opportunities for research. However, many more shapes can be morphed and matched this way than would be possible with conventional methods, and care is needed to generate only the most realistic options. It is therefore essential that any digital reconstruction is carried out with detailed, first-hand knowledge of the original fossil, including how it is preserved and distorted.

This point is particularly relevant with respect to the forward-projecting cheekbones of the newly discovered fossil. After reconstruction, this area looks smoothed, with hardly any sign of the original bone surface. One prominent aspect of MRD where the reconstruction could be improved is the front of the upper jaw. Here, digital processing resulted in a less accurate representation of what the characteristic, strongly projecting subnasal area would have looked like before the fossil was broken.

MRD is a great addition to the fossil record of human evolution. Its discovery will substantially affect our thinking on the origin of the genus *Australopithecus* specifically, and on the evolutionary family tree of early hominins more broadly. This work demonstrates the importance that a single fossil can have in palaeontology, something we should remember when we get puzzled looks and sighs from our colleagues in the experimental biosciences regarding excitement about a sample size of $n = 1$. ■

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METROLOGY

One tick closer to a nuclear clock

Clocks that are based on the nucleus of a single thorium atom could be more precise than existing timekeepers. Such clocks have not yet been realized, but two experiments provide keys steps towards this goal. SEE LETTERS P.238 & P.243

JASON T. BURKE

Atomic clocks are currently the gold standard of timekeeping. These devices measure time on the basis of transitions between two states of an atom. On pages 238 and 243, respectively, Masuda *et al.*[1] and Seiferle *et al.*[2] report progress towards a clock that instead uses transitions between two states of an atomic nucleus. Such a nuclear clock could outperform existing atomic timekeepers, and have applications in both fundamental and applied physics.

Humans have been trying to measure the passage of time for thousands of years. From the sundial, to the hourglass, to the pocket watch, we have continually tried to improve our ability to quantify and standardize time. In the early 1900s, scientists struggled to define time consistently, and put forth various standards to help synchronize humanity. What was missing was a natural reference point that could be used, regardless of its location on Earth. We needed to define what a second truly meant: something fundamental that remains accurate and precise across all space, for all millennia.

Scientists realized that the properties of atomic transitions are independent of location in space or time. This recognition led to the idea of using a known transition between two atomic states as a means to define time. If a standardized second could be defined as a specific and agreed-on number of atomic transitions, time could be quantified. Researchers set out to do this in the 1930s, and by the end of the 1940s the world had its first atomic clock[3].

Over the past 70 years, atomic clocks have been continually improved and currently have a precision[4] of about 1 part in 10^{18}. But what if we could do better than these devices? What if we could make a clock that was 100,000 times smaller, was less susceptible to its environment and possibly had a precision of 1 part in 10^{19}? An atomic nucleus, which is about 100,000 times smaller than an atom, could provide such a device[5].

Since 2003, researchers around the world have been trying to make a nuclear clock using the nucleus of a thorium-229 atom[6]. This nucleus, unlike all others that are known, has an excited state (called an isomeric state) that is only a few electronvolts (eV) in energy above its ground state[7]. As a result, the transition between these two states is accessible using specialized lasers. The problem is that the exact energy of the isomeric state is currently unknown. Masuda *et al.* and Seiferle *et al.* have made progress towards understanding the exact character of the thorium-229 isomeric transition, by carrying out experiments that extend previous work[7].

In Masuda and colleagues' experiment, a high-intensity X-ray beam was passed through a pair of silicon crystals that narrowed the energy range of the X-rays to 0.1 eV. These X-rays were then used to irradiate a thorium-229 nucleus that was in the ground state (Fig. 1). The nucleus transitioned to a second excited state that has an energy much higher than that of the isomeric state. The narrow X-ray energy range allowed the authors to determine the exact energy of

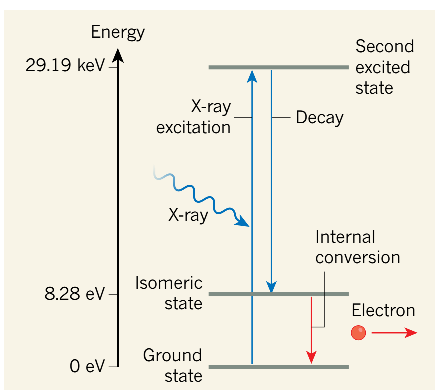

Figure 1 | Low-energy states and transitions of the thorium-229 nucleus. Masuda *et al.*[1] report a technique to produce nuclei of thorium-229 atoms in an excited state called an isomeric state. The authors irradiated a thorium-229 nucleus in the ground state with X-rays, which caused the nucleus to transition to a second excited state that has an energy of 29.19 keV (eV; electronvolts). The nucleus then decayed to the isomeric state. Seiferle *et al.*[2] observed a process known as internal conversion, in which a thorium-229 nucleus in the isomeric state decayed to the ground state and the neutral atom emitted an electron. By studying the energy of emitted electrons, the authors estimated the energy of the isomeric state to be about 8.28 eV. These two studies could lead to ultraprecise clocks that are based on thorium-229 nuclei.

this second excited state: 29.19 keV. Finally, the nucleus decayed directly to the isomeric state. The approach of Masuda *et al.* could enable this state to be produced more efficiently than was previously possible.

In Seiferle and colleagues' experiment, a beam of thorium-229 ions was generated from the natural decay of uranium-233 ions. About 2% of the thorium ions were in the isomeric state. These ions were then neutralized to allow them to decay to the ground state through a process called internal conversion. In this process, a nuclear decay that would typically produce a γ-ray instead causes the neutral atom to emit an electron (Fig. 1). However, internal conversion is complicated, because the electron can originate from many different energy levels in the neutral atom.

To observe the ejected electrons from internal conversion, Seiferle and co-workers used a magnetic field to bend the trajectory of these particles towards an electron detector. They applied an electric field to the electrons until the voltage associated with this field was large enough to stop the electrons. The final voltage was equal to the initial energy of the electrons. Seiferle *et al.* then used a theoretical model to interpret the electron energy spectrum, which is the first energy spectrum observed from the decay products of the isomeric state. Their analysis indicated that the energy of the isomeric state is 8.28 ± 0.17 eV.

Although the ultimate and groundbreaking goal of directly observing the thorium-229 isomeric transition remains elusive, substantial progress continues to be made. The results of Masuda *et al.* and Seiferle *et al.* are key steps forward. Hopefully, the observation is not too far off, as teams of scientists race to make the world's first nuclear clock, which would offer unprecedented precision. This finding would enable a whole host of experiments and discoveries in the decades to follow. For instance, a nuclear clock could have applications in dark-matter research[8] and in the observation of possible variations in the fundamental constants of physics[9]. ■

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SOCIAL SCIENCE

The dynamics of online hate

An analysis of the dynamics of online hate groups on social-media platforms reveals why current methods to ban hate content are ineffective, and provides the basis for four potential strategies to combat online hate. SEE LETTER P.261

NOEMI DERZSY

How does the online hate ecosystem persist on social-media platforms, and what measures can be taken to effectively reduce its presence? On page 261, Johnson *et al.*[1] address these questions in a captivating report on the behaviour of online hate communities that reside on multiple social-media platforms. The authors shed light on the structure and dynamics of online hate groups and, informed by the results, propose four policies to reduce hate content on online social media.

We live in an age of high social interconnectedness, whereby opinions shared in one geographical region do not remain spatially localized, but can spread rapidly around the globe thanks to online social media. The high speed of such diffusion poses problems for those policing hate speech, and creates opportunities for nefarious organizations to share their messages and expand their recruiting efforts globally. When the policing of social media is inefficient, the online ecosystem can become a powerful radicalizing instrument[2]. Understanding the mechanisms that govern hate-community dynamics is thus crucial to proposing effective measures to combat such organizations in this online battleground.

Johnson *et al.* examined the dynamics of hate clusters on two social-media platforms, Facebook and VKontakte, over a period of a few months. Clusters were defined as online pages or groups that organized individuals who shared similar views, interests or declared purposes, into communities. These pages and groups on social-media platforms contain links to other clusters with similar content that users can join. Through these links, the authors established the network connections between clusters, and could track how members of one cluster also joined other clusters. Two clusters (groups or pages) were considered connected if they contained links to one another. The authors' approach had the advantage of not requiring individual-level information about users who are members of clusters.

Johnson *et al.* show that online hate groups are organized in highly resilient clusters. The users in these clusters are not geographically localized, but are globally interconnected by 'highways' that facilitate the spread of online hate across different countries, continents and languages. When these clusters are attacked — for example, when hate groups are removed by social-media platform administrators (Fig. 1) — the clusters rapidly rewire and repair themselves, and strong bonds are made between clusters, formed by users shared between them, analogous to covalent chemical bonds. In some cases, two or more small clusters can even merge to form a large cluster, in a process the authors liken to the fusion of two atomic nuclei. Using their mathematical model, the authors demonstrated that banning hate content on a single platform aggravates online hate ecosystems and promotes the creation of clusters that are not detectable by platform policing (which the authors call 'dark pools'), where hate content can thrive unchecked.

Online social-media platforms are challenging to regulate, and policymakers have struggled to suggest practicable ways of reducing hate online. Efforts to ban and remove hate-related content have proved ineffective[3,4]. Over the past few years, the incidence of reports of hate speech online has been rising[5], indicating that the battle against the diffusion of hateful content is being lost, an unsettling direction for the well-being and safety of our society. Furthermore, exposure to and engagement with online hate on social media has been suggested to promote offline aggression[6], with some perpetrators of violent hate crimes reported to have engaged with such content[7].

Previous studies (for example, ref. 8) have considered hate groups as individual networks, or considered the interconnected clusters together as one global network. In their fresh approach, Johnson and colleagues studied the interconnected structure of a community of hate clusters as a 'network of networks'[9–11], in which clusters are networks that are interconnected by highways. Moreover, they propose four policies for effective intervention that are informed by the mechanisms their study revealed govern the structure and dynamics of the online-hate ecosystem.

Currently, social-media companies must decide which content to ban, but often have to contend with overwhelming volumes of content and various legal and regulatory