

Skepticism Greet Claim of Bubble Fusion

A team of researchers from Oak Ridge National Laboratory, Rensselaer Polytechnic Institute, and the Institute of Mechanics of the Russian Academy of Sciences (RAS) has been using acoustic waves to agitate a flask of deuterated acetone, causing bubbles to expand and contract in phase with the sound. But the researchers really stirred things up in March when they claimed evidence for deuterium-deuterium fusion in their bubbles.¹ Presumably, the shock wave produced by each rapidly imploding bubble was sufficiently intense to force the deuterons together.

So far, however, the evidence proffered by the Oak Ridge-RPI-RAS collaborators, led by Oak Ridge's Rusi Taleyarkhan, has not convinced many observers. As William Moss of Lawrence Livermore National Laboratory put it, "Extraordinary claims demand unambiguous proof."

The critics are not saying that fusion couldn't have occurred, only that its occurrence hasn't been proven. Unlike claims for "cold fusion," the idea of "bubble fusion" does not come out of left field. Bradley Barber, Seth Putterman, and their coworkers from UCLA suggested the possibility in 1994, when they were calculating the shock wave that might develop within a collapsing bubble containing deuterium.² Moss followed with a detailed numerical simulation of a collapsing bubble containing deuterium,³ showing that it might be possible to attain high enough temperatures and pressures to overcome the repulsive forces between deuterons. But doing so requires that the bubble remain spherical long enough for the shock wave to converge tightly at the center. Several groups besides the Oak Ridge-RPI-RAS collaboration are now trying to achieve bubble fusion. But it's not easy to do and it's even harder to prove that it's been done, as Taleyarkhan and coworkers are learning.

The new report attracted predictable media attention because of the association with an energy source. "We're nowhere close to power generation," says Taleyarkhan. Rather, he says, "the main discovery is the use of

Researchers report evidence that fusion has occurred within collapsing bubbles of deuterium-containing vapor. Critics would like to see more definitive proof.

simple classical mechanics to induce and control a nuclear phenomenon."

Sonoluminescence

Interest in bubble fusion has stemmed from work on sonoluminescence (see the article by Lawrence Crum in *PHYSICS TODAY*, September 1994, page 22). That's the light emission from bubbles that develop when a liquid is placed in a sound field: Small bubbles grow during the tensile phase of the acoustic wave and then shrink during its compressive phase. Experimenters have been intrigued by two mysteries: the source of the light emission and its very short duration. Kenneth Suslick of the University of Illinois, an expert in sonochemistry, said that many observers now believe that the light is caused by a combination of high-temperature emissions: photons from excited atoms and molecules, bremsstrahlung from collisions of electrons with atoms or ions, and perhaps black-body radiation.

During typical sonoluminescence experiments, spectral emission tem-

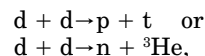
peratures range up to tens of thousands of kelvins, and the rapidly imploding bubble walls can generate internal shock waves under certain conditions. The temperatures and pressures inside the bubble are not known. For fusion to occur, the interior would have to reach millions of kelvins, with pressures of hundreds of megabars.

To promote fusion, Taleyarkhan and company tried to achieve more extreme bubble conditions than in previous sonoluminescence experiments. First, they used deuterated acetone (C_3D_6O) so that fusionable fuel was present. To get a very high compression ratio, they used a beam of energetic (14 MeV) neutrons to generate tiny bubbles in their beaker-sized container of superheated deuterated acetone, estimating that the resulting bubbles will have a minimum radius of 10–100 nm. That's five orders of magnitude smaller than the maximum radius the expanded bubble is expected to reach.

To avoid the resistance to collapse that's frequently produced by residual vapors, the experimenters degassed the acetone. Finally, they drove the liquid with a very intense sound field. Team members performed one-dimensional hydrodynamic shock-code calculations for the conditions of their experiment to determine if fusion was possible.

Signatures of fusion

The fusion of two deuterons (d) can take two equally likely paths:



where t is a tritium nucleus and ${}^3\text{He}$ is a helium-3 nucleus. To prove that fusion has occurred, one should show an increase in tritium and a proportional increase in neutrons having the characteristic energy of 2.5 MeV. To nail the proof, one should demonstrate that the neutrons come out in coincidence with the sonoluminescence generated as the bubble collapses.

After each of three runs of different durations, Taleyarkhan and company took samples from their deuterated acetone to determine how much tri-

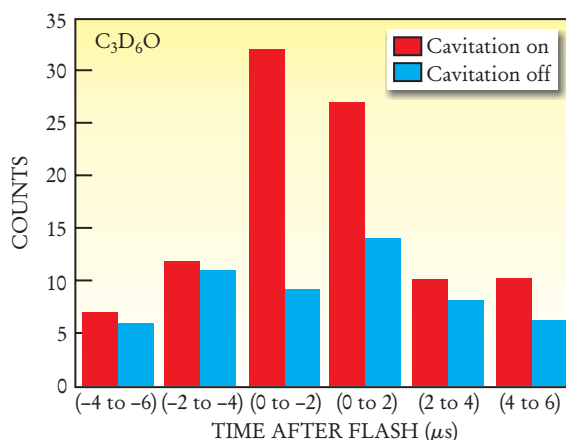


FIGURE 1. COINCIDENCES MEASURED by Taleyarkhan and collaborators. Each count registers the occurrence of a nuclear signal (neutron or gamma) within a specified time after a light flash from a sonoluminescing bubble in a chamber of deuterated acetone. Peaks are seen within 2 μs of the flash, but only when cavitation is turned on. (Adapted from ref. 1.)

tium was present, as measured by its decay rate. For the longest run, the activity was highest: 68.9 ± 2.6 counts/min, compared to the tritium background decay of 53.4 ± 2.3 counts/min. The group estimated that the excess activity corresponds to the emission of $5\text{--}7 \times 10^5$ tritium atoms per second.

Unfortunately, tritium is a notorious and ubiquitous contaminant, and an impurity in deuterated acetone. To check for spurious readings, the experimenters compared results obtained with $\text{C}_3\text{D}_6\text{O}$ to those from runs with normal acetone ($\text{C}_3\text{H}_6\text{O}$). They also did runs with and without cavitation. One would expect elevated tritium levels only when deuterons are present and when sound waves produce cavitation, and that's what the Oak Ridge-RPI-RAS group found.

In searching for 2.5-MeV neutrons that might have been produced by fusion, the Oak Ridge-RPI-RAS team had to cull any fusion neutrons from the substantial background of 14-MeV neutrons used to seed the bubbles. At a rate of 200 pulses per second, the experimenters were sending about one million neutrons per second (n/s) into their chamber.

To determine whether excess neutrons were present, the experimenters used a scintillation counter to detect neutrons as a function of energy, using a pulse-shape discriminator to block out gamma rays. They took the difference in neutron counts with and without cavitation, first for energies at or below 2.5 MeV and then for energies above that. They saw a 4% excess of neutrons below 2.5 MeV, which corresponded to the generation of about $4\text{--}8 \times 10^4$ n/s, about 10 times smaller than the rate of 7×10^5 n/s that would be consistent with the tritium levels they found. Taleyarkhan now estimates that their neutron number would have been higher if his group had corrected for neutron losses within the chamber.

Moss would like to see the full energy spectrum for the neutrons with a maximum energy at the expected 2.5 MeV. Others have expressed concern about the neutron background, because 14-MeV neutrons from the incoming pulse are being scattered around the room and degraded in energy. Taleyarkhan counters that this effect should be the same in runs with or without cavitation.

Putterman points out that the amount of tritium reported by Tale-

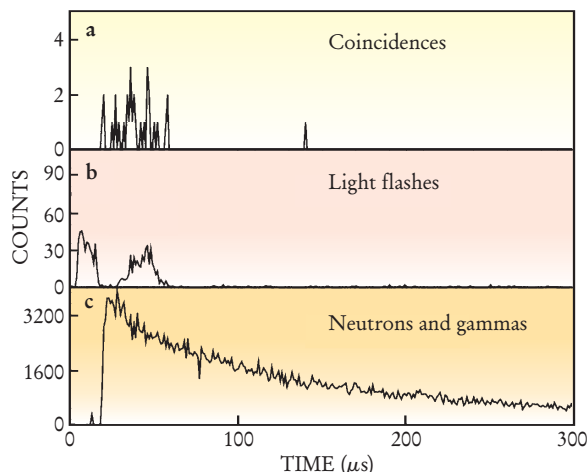


FIGURE 2. OTHER COINCIDENCES, measured by Shapira and Saltmarsh, are consistent with random events. (a) Coincidences between light flashes and neutrons (or gammas). (b) Flashes of light that are not in coincidence with a nuclear signal. (c) Single events (neutrons or gammas), showing the long background tail. (Adapted from ref. 4.)

yarkhan and his team amounts to about 1000 tritium atoms for every incoming neutron that passes through the active region of the cavitation cell. "That's an enormous effect," he says. He's surprised that the best data show a neutron excess of only 4%. Overall, he comments, "the experiment is an excellent example of high-risk, high-gain research. While I can't rule out the existence of a major discovery waiting to be uncovered, the paper does not provide evidence for it."

Coincidence measurements

The final signature of bubble fusion is the coincidence between the sonoluminescent light flashes from collapsing bubbles and the neutron emission. Both should be generated during the final stages of bubble collapse, within a time span much less than 10 ns.

For the coincidence measurements, Taleyarkhan and his collaborators triggered on the sonoluminescent light flash and looked for all signals from a scintillation counter that occurred within a specified time interval after a flash. (The scintillation counter for this measurement recorded both neutrons and gammas.) As seen in figure 1, the coincidence counts peaked in the 2- μs windows surrounding the light flash, but only when the cavitation was on and deuterated acetone filled the chamber.

Of course, a 2- μs window is very wide when one is looking for coincidences between events that occur less than 10 ns apart. Taleyarkhan says

that "our goal was to see if we had a net effect of increased nuclear activity around a sonoluminescence peak."

When Lee Riedinger, a nuclear physicist and deputy director of science and technology at Oak Ridge, learned late last spring about the research by Taleyarkhan and his colleagues, he suggested that the coincidence measurements be repeated by Daniel Shapira and Michael Saltmarsh of the lab's physics division. Shapira and Saltmarsh took data with a bigger neutron detector and more sophisticated electronics, while Taleyarkhan conducted the rest of the experiment.⁴

Shapira and Saltmarsh recorded the time sequence of coincidences between neutrons (or gammas) and light flashes (see figure 2), as well as the time sequence of single light flashes and single neutron (or gamma) events. To best reproduce the results of the Oak Ridge-RPI-RAS collaboration, they set the coincidence window open at 20 μs and looked for coincidences between neutrons or gamma rays, without discriminating between them (although they recorded the pulse height of each count so they could go back later and separate the two).

Shapira and Saltmarsh found that the observed coincidences were consistent with the expected rate of random coincidences. Looking at neutrons only, they reported an increase in background neutron counts for the run with cavitation over that without cavitation, but these counts were not correlated in time with the bubble collapses.

Taleyarkhan and company do not concur with Shapira and Saltmarsh's conclusions. They point out, among other things, that because the pair's detector did not fit within the experimental enclosure, it was placed outside, beyond some shielding. They also feel that Shapira and Saltmarsh's detector threshold was set too high to capture many of the lower-energy neutrons.⁵

In July, Shapira and Saltmarsh wrote up their results for the lab management only. Just before appearance of the Oak Ridge-RPI-RAS paper in *Science*,¹ however, the existence of this second measurement came to light, raising complaints from several *Science* referees that they had not seen all the relevant information. Now the formerly internal report is on the Oak Ridge Web site⁴ and is being prepared for publication.

Richard Lahey Jr, an RPI partici-

part in the experiment claiming fusion, said he's very sure they've achieved d-d fusion. Instead of offering opinions, he says, critics need to try to reproduce their results.

BARBARA GOSS LEVI

How Fast Could *Tyrannosaurus rex* Run?

From Saturday-morning television shows to Hollywood blockbusters, dinosaurs are perennial favorites for inspiring people's curiosity. And topping the fascination list is usually *Tyrannosaurus rex*, the six-ton giant that reigned over the Upper Cretaceous Period 65 million years ago, moving around on hind legs more than 2.5 meters long and devouring less fortunate creatures with its powerful jaws.

Although the fossil record provides clues about some aspects of dinosaur existence, insights into many others must be tortuously teased out of uncovered bones and footprints. Many questions lack direct answers. For example, how fast could dinosaurs move?

That question has proved easier to answer for smaller dinosaurs, whose fossilized footprints contain speed information. In the mid-1970s, McNeill Alexander (University of Leeds) derived a method for estimating speed from the ratio of the stride length to the leg length (which can be determined from recovered bones or estimated from the footprint size).¹ So-called trackways containing stride records have provided evidence for running (having a suspended, aerial phase) for many bipedal dinosaurs.

No trackway evidence of running by larger animals such as *T. rex* has been found, which is not unexpected. It's rare to find fossil beds large enough to span the stride of a running *T. rex*. In addition, most creatures spend much more time walking than running, so any running trackways are rare.

Most estimates of the speed of *Tyrannosaurus* and other large dinosaurs have instead come from various comparisons to other vertebrates. Noting the similarity of *T. rex* skeletal anatomy to that of extant birds and other fast runners, Gregory Paul and Robert Bakker have suggested that *T. rex* would have been able to run at least 20 m/s (45 mph).²

Applying more physics-based arguments, others have proposed slower maximum speeds. Based on the max-

References

1. R. P. Taleyarkhan, C. D. West, J. S. Cho, R. T. Lahey Jr, R. I. Nigmatulin, R. C. Block, *Science* **295**, 1868 (2002).
2. B. P. Barber, C. C. Wu, R. Löfstedt, P. H. Roberts, S. J. Putterman, *Phys. Rev. Lett.* **72**, 1380 (1994).
3. W. Moss, *Phys. Lett. A* **211**, 69 (1996).
4. D. Shapira, M. J. Saltmarsh, <http://ornl.gov/slsite/SLan5av2.pdf>.
5. R. P. Taleyarkhan R. C. Block, C. D. West, R. T. Lahey Jr, <http://www.rpi.edu/~laheyr/SciencePaper.pdf>.

A new biomechanics model finds that *T. rex* lacked large enough leg muscles to run fast.

imum transverse forces that *T. rex* bones could have withstood, Alexander has argued that it was capable of a modest run at best.³ Per Christiansen (University of Copenhagen), quantifying such arguments, estimated that *T. rex* could walk at 10 m/s (22 mph)—still far from slow.⁴ James Farlow (Indiana-Purdue University) and colleagues⁵ have suggested that a fast-running *T. rex* would have experienced fatally large forces if it had tripped, so they concluded it likely moved no faster than 10 m/s.

Working at the University of California, Berkeley, John Hutchinson

(now at Stanford University) and Mariano Garcia (now at Borg Warner Automotive in New York) recently offered a new approach for analyzing possible speeds of *T. rex* and other bipeds, based on a biomechanical model for determining the minimum mass of leg extensor muscle required for an animal to run.⁶ With this model, the pair found that *T. rex* could not have had strong enough legs to be a fast runner.

Scaling muscles

Underlying this new model is the observation that muscles in vertebrate animals generate remarkably uniform maximum force per unit cross section, about 300 kN/m². Given that evolution has conserved this muscle property, Hutchinson and Garcia argue it's reasonable to assume that the muscles of dinosaurs such as *T. rex* had similar force-generating capability.

One consequence of this uniformity is that muscle strength increases more slowly than muscle mass as body size increases, as roughly the ²/₃ power rather than linearly. Thus, as body size increases, the muscle mass needed to support and move it increases even faster. This scaling difference, well-known for decades, is at the core of the researchers' conclusion that *T. rex* was not a fast runner.

Hutchinson and Garcia use a two-dimensional free-body diagram to determine the minimum muscle mass per leg that's needed at midstride to maintain quasistatic equilibrium, factoring in the forces and torques from various muscles, limb segment weights, and the ground (see figure 1).

At the midpoint of the running stride, the body is at its lowest point, accelerating upward. The necessary upward force comes from the ground. For extant bipeds at a fast run, this ground reaction force (GRF) is about 2.5 times the body weight, relatively independent of species or mass. Hutchinson and Garcia therefore adopted this relation for their calculations.

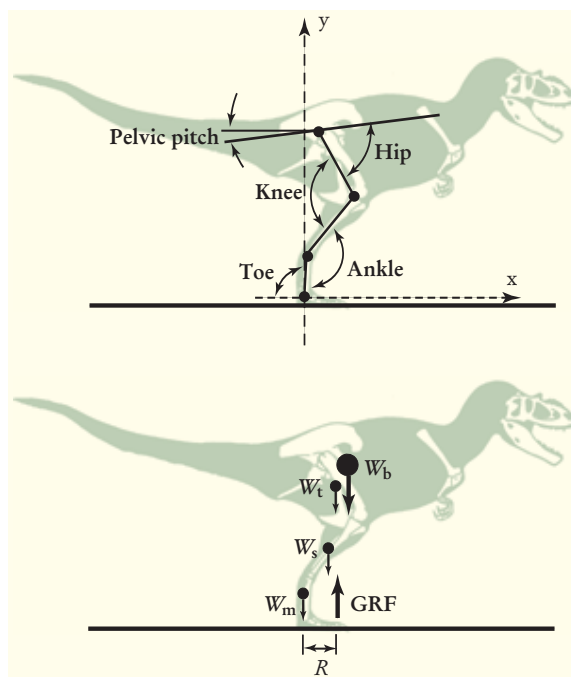


FIGURE 1. IN A FREE-BODY DIAGRAM for a running tyrannosaur, the angles of the leg joints (top) are critical parameters. In addition to the forces and torques produced by leg muscles, external forces (bottom) including the weights of the body (W_b), thigh (W_t), shank (W_s), and metatarsus (W_m), as well as the ground reaction force (GRF) that acts a distance R from the toe joint must be incorporated. (Adapted from ref. 6.)