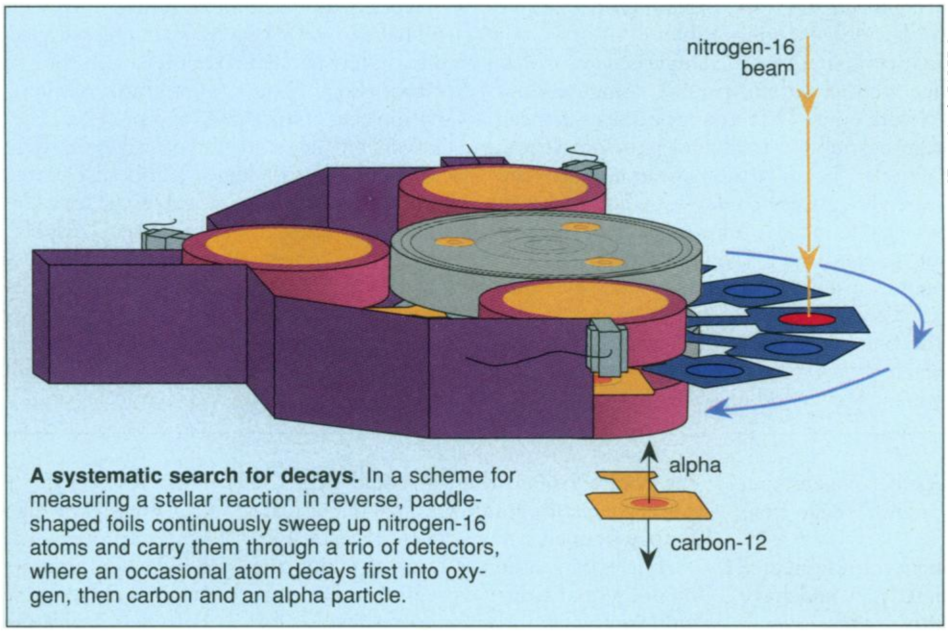
ASTROPHYSICS

Pinning Down a Missing Link in Massive Stars

You could hardly guess from the title of the paper in the 8 February issue of *Physical Review Letters* that it would be avidly read by more than a small circle of nuclear astrophysicists. But its arcane language—"The beta-delayed alpha-Spectrum of ^{16}N and the ^{12}C(alpha, gamma)^{16}O Cross Section at Low Energies"—signaled that a long quest to solve what Caltech nuclear physicist William Fowler, in his 1983 Nobel address, called "a problem of paramount importance" was finally coming to an end. What a mostly Canadian team led by nuclear astrophysicists Richard Azuma of the University of Toronto, Lothar Buchmann of the TRIUMF laboratory in Vancouver, and Charles Barnes of the California Institute of Technology had measured was the key factor determining how fast massive stars fuse helium and carbon to make oxygen. This single reaction is crucial to understanding the lives of massive stars and the origin of the heavy elements in the universe.



A systematic search for decays. In a scheme for measuring a stellar reaction in reverse, paddle-shaped foils continuously sweep up nitrogen-16 atoms and carry them through a trio of detectors, where an occasional atom decays first into oxygen, then carbon and an alpha particle.

The paper marks the endpoint of 20 years of speculation about a nuclear reaction rate so difficult to measure that the existing estimates, as Barnes puts it, had been "ridiculously uncertain." And it marks the end of a tight race to come up with the elusive measurement. Working at the TRIUMF accelerator, the group solved the measurement problem by combining new theoretical work with a clever experimental end-run. Hot on their heels was another experimental group led by Moshe Gai of Yale University, which came up with more or less the same result. And both experiments were in line with the results of a third team, Stan Woosley of the University of California, Santa Barbara, and Tom Weaver of the Lawrence Livermore Laboratory, who had calculated the reaction rate using a theoretical model. The TRIUMF experiment alone was enough to convince Nobel laureate Hans Bethe of Cornell University, however: "[It] is ingenious, well carried out, and I believe the result."

Bethe and other astrophysicists have longed to know this rate—called the S-factor—because it is a key to understanding the workings of the universe's element factories: the stellar interiors where lighter nuclei are fused into heavier ones. Unlike our sun, which can burn only hydrogen and helium, massive red giant stars can burn successively heavier elements, running the gamut through carbon, neon, oxygen, and silicon to iron. At the end of their lives, the massive stars explode as supernovae, forging the remaining heavy elements and scattering the newly minted nuclei through the interstellar medium, where they provide the ingredients of new stars and solar systems.

Two of the reactions in this evolution occur at about the same temperature in stellar furnaces and compete for helium fuel. One fuses three helium nuclei, known as alpha particles, to form carbon. The other fuses carbon and an alpha particle to form oxygen. The relative rate of these two reactions is key to all that follows. "The entire future history of a star," says Caltech's Barnes, "right up through the supernova stage, depends on the relative amounts of carbon and oxygen you make."

Carbon and oxygen, explains Weaver, are the prime fuels for the phases of stellar evolution that generate the intermediate mass isotopes—those from oxygen through calcium in the periodic table. The ratio in which carbon and oxygen are produced determines the relative abundances of all these isotopes in the universe. In addition, says Weaver, if oxygen burning dominates in massive stars, their cores tend to be larger, and it is more likely that, when the stars explode at the end of their lives, the remaining "cinders" will be black holes, rather than neutron stars.

The rate of the carbon-forming reaction has been known for years. But the oxygen-forming reaction could not be measured directly. Physicists can't recreate stellar temperatures and pressures, though they can simulate them by slamming nuclei together in accelerators. The catch is that the energy equivalent to the relevant stellar temperature—200 million degrees Kelvin—is only 300,000 electron volts (300 KeV). In red giant stars, with a tremendous density of carbon and helium nuclei, that energy is enough for furious nuclear burning. On Earth, even with the strongest conceivable 300 KeV alpha beam and the purest carbon target, collisions would be so rare that one would be lucky to observe a single fusion a year. Notes Barnes, "Nobody in the world knows how to measure that reaction at such low energies."

With most nuclear reactions, it would be possible to extrapolate downward from the rate at higher energies to the rate at 300 KeV, but this reaction has an extra twist that makes extrapolation virtually impossible: Oxygen nuclei have two excited states at energies very close to the energy required for fusion. Fusion speeds up near the energy of an excited state, and physicists expected that together, the excited states might influence the fusion rate at stellar temperatures. Somehow, nuclear physicists had to measure the effect of these excited states. They've been able to do so for the higher excited state. But the lower one—known as a subthreshold resonance—exerts its effect at such low energies, where fusions are so rare, that measuring it seemed out of reach. Yet this resonance is likely to be the major influence on carbon-helium fusion in stars.

A back door opens. Around 1970, Barnes and Fowler, and independently Fred Barker of the Australian National University, began speculating about what Azuma calls "a back-door way of getting at the carbon-12 reaction." These physicists knew that radioactive nitrogen-16, as it decays into oxygen, sometimes yields an oxygen nucleus in an excited state that undergoes a second decay to carbon-12 and an alpha particle. That second decay would in effect play out the carbon-helium fusion in reverse. And because oxygen spawned by the nitrogen decay might sometimes have just the right energy to feel the influence of the subthreshold resonance—what Barker whimsically called "the ghost"—one might conceivably measure the ghost by studying the subsequent decay of the oxygen.

To do so, experimenters would have to measure the energies of the carbon and alpha particles and obtain a spectrum of the decay rate; hidden in that spectrum would be the signature of both excited states—or at least part of the signature. The oxygen decay isn't a perfect inverse of the fusion. As a result, only one component of the ghost (known as E1) would manifest itself in the decay; the other, most likely smaller, component (E2) would not make an appearance. Even getting that far, however, would require extraordinarily sensitive detectors as well as a deeper understanding of the underlying nuclear physics than was available when Barker, Barnes, and Fowler began speculating about the back door.

As a result, the research languished for more than a decade, until a flurry of theoretical activity beginning in 1988 revived it. First two Belgian theorists, D. Baye and P. Descouvemont, published what's called a microscopic nuclear calculation—an effort, explains Azuma, "actually to look at interactions between neutrons and protons that exist in oxygen-16 and then try to calculate how breakup [into carbon and helium] might go about." Close behind followed a paper from a Caltech collaboration that included Xiangdong Ji, Bradley Fillipone, Jean Humblet, and Steve Koonin. Both papers predicted that the ghost would be visible in the oxygen's decay spectrum as a tiny peak about three orders of magnitude smaller than the peak from the higher excited state. When Azuma read the Caltech paper, he says, "it hit me there was this little bump, this ghost down below, which might be measured. It was a ripe plum ready for the picking."

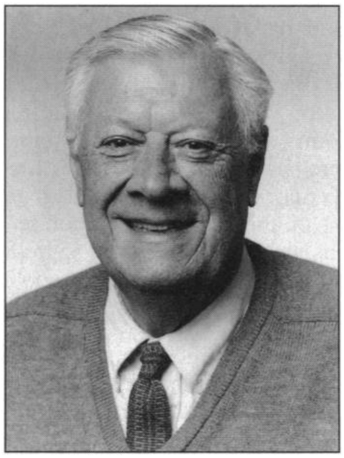
And the place to pick it, Azuma, Barnes, and Buchmann decided in 1989, was TRIUMF, an accelerator in Vancouver equipped with an isotope separator that could produce extremely pure beams of ions such as nitrogen-16. The team was not alone in noticing that the plum was ripe, however. Across the continent, Yale nuclear physicist Moshe Gai and his students also saw the Caltech paper, and they immediately set to work redesigning an ongoing experiment to pursue the resonance.

Both teams realized that it would not be easy. Most of the time, the nitrogen-16 would decay into stable oxygen; only 1 in 100,000 of these decays would yield oxygen in an excited state that could break up into a carbon-12 and an alpha particle. Most of those decays would reflect only the higher-energy excited state; only a tiny fraction would feel the influence of the ghost. "The experimental problem," says Lothar Buchmann, "is to measure something very small on the low-energy side of something very big."

To do so, the experiment would have to distinguish alpha particles emitted by the ghost from the much more abundant, higher-energy ones tracing the main peak. And there was ample opportunity for confusion—from the higher-energy alphas, a small fraction of which might get degraded somehow in the detector and appear as a ghost-emitted alphas, and from the copious electrons emitted by the nitrogen-16 decays.

Picking the plum. These problems stymied the TRIUMF group for 2 years—through December 1991. Meanwhile Gai and his students had been making progress using a detector scheme that identified oxygen-16 decays by recognizing the coincidence of an electron from the nitrogen-16 decay and an alpha particle, which had to come from the oxygen-16. Says Azuma, "Every glitch we had, we said, 'Oh my god, Moshe Gai's going to get it first.' "

Finally, one late night toward Christmas 1991, the TRIUMF group figured out how to get rid of the electron background. They decided to replace the standard particle detectors, hundreds of microns thick, with ones just 10 microns thick. Electrons would pass through these detectors virtually unnoticed, while alpha particles and carbon nuclei, heavily charged and heavily ionizing, would stop and deposit all their energy even in 10 microns. To eliminate the other source of confusion—degraded alpha particles—they planned to mount these detectors on opposite sides of the film that would collect the nitrogen-16. Since a decaying oxygen would fling an alpha particle and a carbon nucleus in opposite directions to conserve momentum, the tandem detectors could correlate the products of each decay. And because any real event would yield an alpha carrying three times as much energy as the carbon, any events without that ratio could be promptly rejected as alpha particles somehow degraded from the main peak. Asks Azuma, "What could be simpler or more elegant than that?"


Ghostbuster. Caltech's Barnes helped measure the elusive decay.

The TRIUMF team gathered data from the end of May through 10 July—a million oxygen-16 decays in total, out of which some 1500 to 2000 make up the ghost; the paper went to *Physical Review Letters* on 4 November. The Yale paper was submitted a week later with somewhat less impressive statistics: 55,000 decays, with about 200 events in the ghost. Nonetheless the two results are in reasonably good agreement. The TRIUMF measurement implies an S-factor (based only on the E1 component of the ghost) of 57 ± 17 KeV-barns—a measure of the likelihood of the reaction—while the still-unpublished Yale result is 95 ± 34.

Those results mean that theorists' understanding of how massive stars evolve and make elements is on the right track, says Tom Weaver. He should know; last summer, he and Stan Woosley tried to work backward from the observed abundances of elements in the solar system to infer the stellar element-forming processes that must have been responsible. In a computer model of a massive star, the two astrophysicists tested "thousands upon thousands of nuclear reaction rates," says Weaver, to see which ones generated something close to the observed pattern of elements.

To Weaver and Woosley's astonishment, they were able to arrive at a single, coherent picture of a massive star's inner workings that explained the observed abundances of 15 major isotopes, from oxygen to calcium. "We couldn't believe it when it was first plotted," says Weaver. "We couldn't believe how good it was. It was incredible how many things could be explained in the same general unified model."

It worked, however, only for a specific value of the S-factor, says Weaver: "That nice result is critically dependent on the [carbon-helium fusion] rate." And the value that worked best, Weaver and Woosley will report in an upcoming issue of *Physics Reports*, was 170 ± 50, with both the E1 and E2 components included. But Weaver puts more stock in actual measurements, and he's gratified that the experimental results are in the same ballpark. Assuming the E1 and E2 components of the reaction are roughly similar, the TRIUMF measurement of 57 ± 17 for E1 becomes 114 ± 34 for both components.

But Barnes and his colleagues don't want to leave anything to chance. As much as half of the ghost—the E2 component—is still at large, and they are casting around for ways to snare it. Koonin and his colleagues have suggested several ways this could be done, none of which is particularly easy but all of which are doable. "It's certainly in the cards," says Barnes. Having found one back door into giant stars, he's confident that more are waiting to be opened.

–Gary Taubes