Rare nuclear transition provides evidence for stellar explosion mechanism

Rachel Berkowitz

Citation: Physics Today **73**, 3, 16 (2020); doi: 10.1063/PT.3.4425
View online: https://doi.org/10.1063/PT.3.4425
View Table of Contents: https://physicstoday.scitation.org/toc/pto/73/3
Published by the American Institute of Physics

close enough to Earth for many hundreds of years. Cepheid variable stars can bridge that gap. They're both numerous enough to be well represented near Earth and bright enough to be visible at the same distances as the nearest supernovae. As discovered by Henrietta Leavitt a century ago, Cepheids' luminosities are related to their pulsation periods, so their relative distances can be inferred from their apparent brightness.

SH0ES has been shoring up the links between parallax, Cepheids, and supernovae, and other groups have checked and rechecked them. But there remained the possibility that some aspect of the underlying physics—of supernova evolution, Cepheid pulsation, or the telescopes used to observe them—wasn't understood as well as astronomers thought it was.

It's important, therefore, that H0LiCOW and SH0ES get the same answer from independent methods. SH0ES's measurement has nothing to do with gravitational lensing or modeling of galaxy mass distributions, and H0LiCOW's has nothing to do with the mechanisms of Cepheids or supernovae. If SH0ES's result is marred by a systematic error, H0LiCOW's analysis would have to coincidentally include a different error of almost exactly the same magnitude and sign.

Discovery?

In high-energy physics, a signal with statistical significance of 5σ is the threshold for claiming discovery of a new particle or effect. (See, for example, PHYSICS TODAY, September 2012, page 12, and August 2019, page 14.) The statistical meaning of a 5σ result is the same in all contexts: Assuming a Gaussian distribution of measurement fluctuations, there's a 1 in 3.5 million chance that the result could arise by statistical fluctuations alone, in the absence of any underlying effect.

But cosmologists so far have been reluctant to declare that the tension in H_0 measurements must be a sign of physics beyond the ΛCDM model, in part because it's not at all clear what that physics would be. There aren't many ways the ΛCDM model could be modified that would both close the H_0 gap and maintain the model's agreement with all other measurements. Some of the possibilities theorists are exploring include dark radiation (relativistic dark particles, such as sterile neutrinos, whose wavelengths get stretched as the universe expands), non-Newtonian modifications to gravity, or a dark energy that's not constant. But there's no specific evidence, yet, of any of them, and a complete theoretical picture remains elusive.

The H0LiCOW researchers are working on adding more quasars to their analysis, with the goal of reducing their measurement uncertainty below 1%, or 0.7 km/s/Mpc. If their H_0 value remains unchanged, such a measurement would be 5σ different from the ΛCDM on its own, independent of SH0ES or any other result.

Johanna Miller

References

1. Planck collaboration, https://arxiv.org/abs/1807.06209 (2018).
2. A. G. Riess et al., *Astrophys. J.* **876**, 85 (2019).
3. V. Bonvin et al., *Mon. Not. R. Astron. Soc.* **465**, 4914 (2017).
4. K. C. Wong et al., *Mon. Not. R. Astron. Soc.* (in press).
5. S. Refsdal, *Mon. Not. R. Astron. Soc.* **128**, 307 (1964).

Rare nuclear transition provides evidence for stellar explosion mechanism

With its higher-than-expected propensity to capture electrons, neon could drive some stars' thermonuclear death.

When the core of a massive star runs out of nuclear fuel, it collapses under its own gravity to form a neutron star or a black hole and sheds its outer layers in a supernova. (See, for example, the article by Hans Bethe, PHYSICS TODAY, September 1990, page 24.) However, for smaller stars in the 7- to 11-solar-mass range, gravitational collapse may not be the only possible route to a supernova. Those stars are abundant in our galaxy, but the final phase of their evolution is unclear. Some may undergo gravitational collapse like massive stars. But if nuclear reactions in a star's core generate sufficient energy to counter collapse, its life may also end in a thermonuclear

FIGURE 1.OLIVER KIRSEBOM, KNEELING AT COMPUTER, AND COLLEAGUES designed an experiment at the University of Jyväskylä accelerator laboratory in Finland to measure how frequently radioactive fluorine-20 emitted electrons and decayed to ground-state neon-20. The photo was taken at 1444 m depth in the underground laboratory. (Image courtesy of Oliver Kirsebom.)

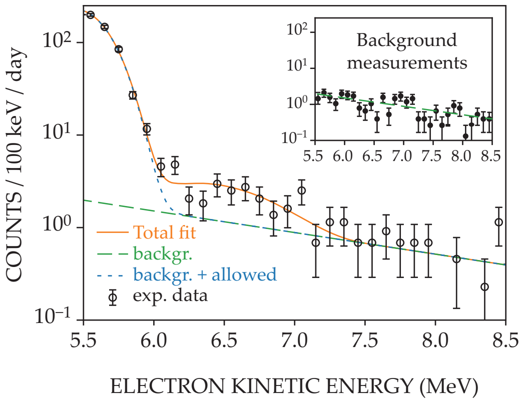

FIGURE 2. THE ENERGY SPECTRUM MEASURED DURING RADIOACTIVE DECAY of fluorine-20 to neon-20 (orange) shows the count of electrons emitted at different energies during 105 hours of decay. Below 5.4 MeV, the count exceeded that emitted by background sources (green), as predicted by simulations (blue). Between 5.4 MeV and 7 MeV, the measured count exceeded the predicted count; that difference indicated occasional occurrence of ^{20}F decay to ground state ^{20}Ne. The inset showing the background spectrum obtained without the ^{20}F beam confirms the forbidden transition's contribution to the spectrum. (Adapted from ref. 1.)

explosion that ejects some material while leaving behind a white dwarf remnant.

To understand the fate of a star, astrophysicists must delineate the nuclear reactions that occur in its core after the main fuel-burning cycle ends. At that point, stars in the range of 7–11 solar masses have cores that consist mainly of oxygen and neon. Theoretical models of stellar evolution predict which reactions happen next. Particularly important is a reaction sequence in which an atomic nucleus absorbs an electron, which combines with a proton to form a neutron. In that sequence, a high-energy (7 MeV) electron is absorbed by neon-20 to form fluorine-20, which promptly captures another electron to form oxygen-20. As a by-product of that reaction chain, gamma radiation is released and heats the stellar core enough to trigger the ignition of oxygen. Whether the energy liberated by oxygen ignition is enough to forestall collapse or trigger an explosion depends critically on the density at which the onset of electron capture on ^{20}Ne takes place.

A team led by Oliver Kirsebom (now at Dalhousie University in Nova Scotia, Canada) and Gabriel Martínez-Pinedo (GSI Helmholtz Center for Heavy Ion Research and Technische Universität Darmstadt in Germany) has recently found that the electron capture on ^{20}Ne occurs at lower densities and with a higher rate than previously expected. The researchers inferred experimentally the chain's first and rate-limiting step—the capture of electrons by ^{20}Ne—under conditions that prevail in a stellar interior. Stellar models based on the new rate suggest that thermonuclear explosion is the common end for many of our galaxy's stars.[1,2]

Forbidden transition

Atomic nuclei have different energy states. Which one a nucleus is most likely to inhabit depends on the temperature and density of the environment. At the temperatures in oxygen–neon stellar cores, most ^{20}Ne exists in its ground state. As the stellar core evolves, its density grows and the energy of the electrons, which comprise a degenerate gas in the core, increases. At some point, electrons will have enough energy, 7 MeV, to link in a decay chain the ground states of Ne and F.

The rate at which Ne captures electrons during the transition between the ground states of ^{20}Ne and ^{20}F nuclei can be directly related to the inverse process, the beta-decay in which radioactive ^{20}F emits an electron and produces ^{20}Ne. Under terrestrial conditions, ^{20}F decays to the first excited state of ^{20}Ne. However, that ground state transition has an extremely low likelihood and is considered forbidden. Forbidden means that the reaction links nuclear states with different spins, which results in a transition that is, in this case, supressed by six orders of magnitude compared to an allowed transition between same-spin states. As a result, quantifying the rate-limiting electron capture step is difficult.

To learn more about the neon–fluorine electron capture rate, Kirsebom and colleagues looked to an allowed version of the inverse beta-decay process. The decay that connects ^{20}F decays to the first excited state of ^{20}Ne can produce electrons that have from zero to 5.4 MeV of kinetic energy, whereas the decay connecting the ground states of ^{20}F and ^{20}Ne produces electrons up to a maximum kinetic energy of 7 MeV.[3] Electrons with energies up to 5.4 MeV mostly originate from the allowed decay to the excited state of ^{20}Ne; but any electrons with energies above 5.4 MeV must originate through the forbidden ground state decay. Kirsebom designed an experiment to measure how frequently ^{20}F emitted electrons with energies above 5.4 MeV, and thereby determine the strength of the forbidden transition.

Earthly measurements

Because ^{20}F decays extremely rapidly, with a half-life of 11 seconds, studying its behavior requires an advanced accelerator facility where the isotopes can be produced and quickly transported to a detection system. At the University of Jyväskylä accelerator laboratory in Finland the researchers bombarded carbon foil with a beam of ^{20}F nuclei. The laboratory is one of the few facilities worldwide that can produce a pure, intense, low-energy ^{20}F beam, free of contamination by other radioactive isotopes. On striking the carbon foil, the ^{20}F nuclei became embedded. Kirsebom and his colleagues, shown in figure 1, monitored the nuclei as they decayed and emitted energetic electrons. A specially designed scintillator detector with a magnetic transporter measured the electrons' energies.

The team paid particular attention to electrons that had kinetic energies 5 MeV and above. The resulting energy spectrum in figure 2 shows the count of electrons emitted at each energy during 105 hours of data collection. For energies below 5.4 MeV, the electron count exceeded by five orders of magnitude that emitted by background sources. The spectrum matched that obtained by simulations, which indicated frequent occurrence of the allowed decay of ^{20}F to excited ^{20}Ne. The background count rate was determined in separate measurements made with precisely the same setup but without the ^{20}F beam. Between 5.4 MeV and 7.0 MeV, the measured number of counts exceeded that expected from background sources. Electrons at those energies indicate occurrence of the forbidden decay of ^{20}F to ground state ^{20}Ne. For energies above 7 MeV, the entire electron count came from background cosmic rays. "Just looking at the large number of counts observed, one realizes that we are dealing with a rather strong forbidden transition," says Kirsebom.

The researchers concluded that 1 in 250 000 events produced ^{20}Ne in its ground state—a rate that should match that of the reverse process. Based on the measured transition probability, and

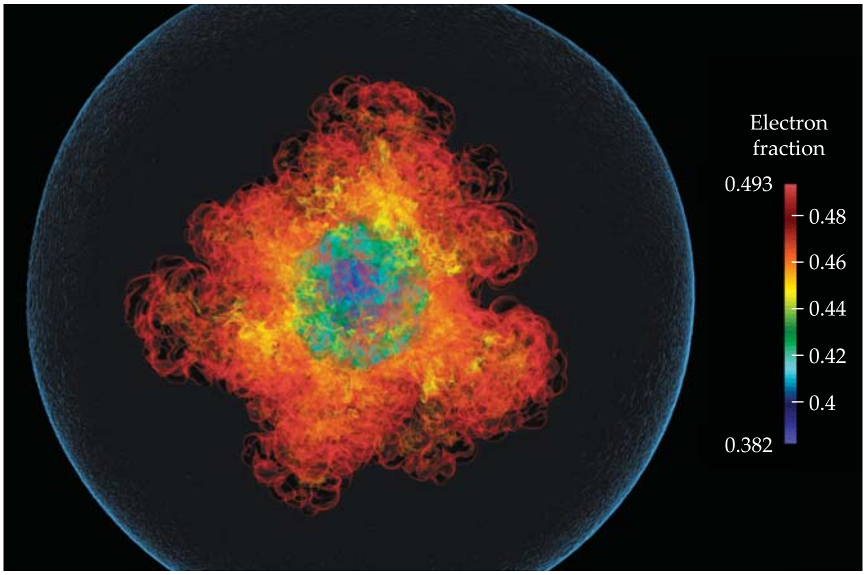

FIGURE 3. NUMERICAL SIMULATIONS SHOW THE SUPERNOVA that results from an oxygen–neon stellar core after the newly measured neon-20 electron capture triggers a thermonuclear explosion. The color key shows the explosion's electron fraction, which describes whether isotopes tend to be richer in protons or neutrons. For example, iron-56 has 26 protons and 30 neutrons, so its electron fraction is 26/56 or 0.464 and corresponds to the orange regions of the explosion. Iron-60 has an electron fraction of 26/60 or 0.433, corresponding to the turquoise region. The lowest electron fraction achieved in the simulation (blue) is below 0.40, which is 12% lower than regular supernovae. (Adapted from ref. 5.)

considering stellar plasma densities of 10^9 g/cm^3, electron capture on ^{20}Ne was determined to occur eight orders of magnitude more often than assumed by previous calculations.

Stellar implications

Numerical simulations of stellar evolution that take into account the newly measured Ne–F transition rate suggest that the star's core begins to generate heat earlier than previous models predicted.[4] Once the core reaches 1.5×10^9 K, oxygen can fuse with itself; the earlier ignition happens, the higher the likelihood of a thermonuclear explosion.

The resulting supernova, like the one simulated in figure 3, differs from the type II supernova that ends the life of a star more massive than 11 solar masses. It also differs from the type Ia supernova in which a carbon–oxygen white dwarf fully explodes. It ejects more mass and it leaves behind an iron-rich white dwarf, as opposed to a neutron star or black hole.[5] The proportion of ejected elements also differs from both other supernova types; it is richer in calcium-48, titanium-50, chromium-54, and iron-60.

By itself, a high Ne–F transition rate isn't enough to preordain the explosion of a 7- to 11-solar-mass star. The energy released by electron capture on ^{20}Ne may trigger convection in the stellar core. Convection leads to mixing and could delay the onset of oxygen ignition, so that gravitational collapse would be the end of the star. Improved models of convection in the stellar core are needed.

The observation of iron-rich white dwarfs would clinch the case that the Ne–F transition drives a thermonuclear explosion. Several candidates have already been detected through observations of their atmospheres.[6] The associated explosions are expected to be characterized by specific spectral features that could, in principle, be observed.[5]

Rachel Berkowitz

References

1. O. S. Kirsebom et al., *Phys. Rev. Lett.* **123**, 262701 (2019).
2. O. S. Kirsebom et al., *Phys. Rev. C* **100**, 065805 (2019).
3. G. Martinez-Pinedo et al., *Phys. Rev. C* **89**, 045806 (2014).
4. J. Schwab, E. Quataert, L. Bildsten, *Mon. Not. R. Astron. Soc.* **453**, 1910 (2015).
5. S. Jones et al., *Astron. Astrophys.* **622**, A74 (2019).
6. R. Raddi et al., *Mon. Not. R. Astron. Soc.* **489**, 1489 (2019).

Doubt is cast on a mechanism of cancer nanomedicine

Leaky blood vessels seemed like the perfect conduit to deliver cancer-fighting drugs selectively to tumors. But the reality is starting to look more complicated.

Cancer is a disease of tissue growth gone wrong. Tumor cells proliferate uncontrollably and don't die as they should. When a solid tumor grows large enough to need to sprout its own blood vessels, those vessels, too, grow irregularly. The tumor vessel networks are tortuous and disorganized (see PHYSICS TODAY, February 2016, page 14), and the vessels' lining, or endothelium, is riddled with gaps hundreds of microns wide between cells.

The challenge of chemotherapy is to kill off the tumor cells without doing too much harm to healthy ones. The interendothelial gaps promised a way to do that. Nanoparticles up to 300 nm in diameter can fit through the gaps, and they can't permeate normal blood vessels the same way. So nanoparticles loaded with a drug should, it stands to reason, selectively enter and attack tumor tissue but leave healthy tissue alone. An inherently biomedical challenge was seemingly transformed into one of nanotechnology and fluid dynamics.

A quarter century of nanomedicine research has indeed yielded a few nanoparticle drug formulations that offer better performance or fewer side effects than their molecular counterparts. (See the article by Jennifer Grossman and Scott McNeil, PHYSICS TODAY, August 2012, page 38.) The mechanism of their action, however, has never been fully verified. No technique exists that can image nanoparticles *in vivo*, in real time, and with sufficient resolution to observe the particles slipping through the inter-