On the origin of life's most crucial isotope

12 October 2012, by Ken Kingery

Since the Big Bang, the universe has been evolving. From the formations of simple protons and neutrons to the wide breadth of elements and molecules known today, it is ever growing in complexity and variety. And now, nuclear physics theorists have gained new insights into a fundamental nuclear reaction that gave rise to life as we know it.

The reaction is known as the triple-alpha process and it is responsible for the large amount of carbon found throughout the universe. For years, the process by which stars combined light, simple nuclei into the most crucial element has been understood only as a two-step process. But recently, the problem was revisited to unveil the full scope of mechanisms behind the formation of life's most crucial isotope, carbon-12.

Specifically, that problem was the rate of carbon-12 production at low temperatures. Previous calculations made by a group led by Kazuyuki Ogata, professor of nuclear physics from Kyushu University in Fukuoka, Japan, resulted in dramatic models where stars would burn up so fast that they could not reach the red giant phase.

A problem, seeing as how there are plenty of red giants to be found throughout the cosmos.

"The Kyushu theory predicting rates of carbon-12 production were incompatible with observations and the whole nuclear astrophysics community was going bezerk," said Filomena Nunes, nuclear physics theorist and professor at NSCL. "I was getting emails all over the place. The method being used was sound and the Kyushu group members are experts on that method. So there had to be something wrong with the approximations."

Carbon is the fourth most abundant element in the universe, and carbon-12 is its most common form. With an even number of six protons and six neutrons, this simple nucleus forms the basis of all known life. However, the processes that create carbon-12 and the reasons for its abundance are not so simple.

In a matter of microseconds after the Big Bang, quarks and gluons formed protons and neutrons. Just three minutes later, simple hydrogen and helium nuclei came on the scene. But it wasn't until one million years later that electrons joined the party to form neutral atoms and ten billion years after that until stars began to form.

Within the cauldron of a star, protons began combining through a sequence of reactions into helium nuclei. But then the nuclear synthesis process came to an impasse. Add another single proton to helium and you get lithium-5, a nucleus that nature does not permit to exist. Fuse two helium nuclei together and you get beryllium-8, another non-existent nucleus due to the laws of nuclear physics.

But clearly the stars continued churning away, creating all the different elements we see around us. So how is this possible? This question nagged astrophysicists for years because, NSCL graduate student Ngoc Bich Nguyen said, "If we cannot explain the abundance of carbon-12, we cannot explain how our universe formed."

The answer comes in the form of a reaction involving three helium nuclei, also known as alpha particles. Though beryllium-8 decays in mere nanoseconds, if a star is hot enough, a third alpha particle can fuse with the short-lived nucleus. And because the energy of a beryllium-8 nucleus added to the energy of an alpha particle is almost exactly the same as a carbon-12 nucleus in an excited state, it creates a resonance that greatly increases its rate of production.

But there is another way that stars can create carbon-12.

At low temperatures, when the energy is not enough to reach the resonances, carbon-12 can still be formed through the simultaneous fusion of three alpha particles. And while in the past, nuclear theory accurately modeled the rates of the two-step process, it was woefully inaccurate when it came to the single-step process. The Kyushu group made a serious improvement on those predictions.

"However their results prohibited the formation of red giants, which we know exist because we've observed them," said Nunes. "So I had the idea for an alternative approach without the limitations of the one that was being used at the time."

Together, Nunes and Nguyen solved this very challenging three-body scattering problem. When their new results were obtained, they agreed with the prior theory for high-temperature carbon-12 formation. At lower temperatures, however, they predicted an increase of the rate by about 10 trillion times from the estimates from the past.

While this seems like a lot, it still was much less than Ogata's predictions.

"With our new results, red giants finally exist again!" said Nunes. "From here, we have to use the new rates in many more astrophysical scenarios. We hope it will resolve some issues lingering in novae and supernovae."

More information: Low-Temperature Triple-Alpha Rate in a Full Three-Body Nuclear Model, *Physical Review Letters*, 109, 141101 (2012) prl.aps.org/abstract/PRL/v109/i14/e141101

Provided by Michigan State University