COMMENTARY

From deep earth to deep stars: A different nuclear reaction path to generate calcium in ancient stars

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A recent study by Zhang et al.[1] reported a successful direct measurement of the ^{19}F(p,γ)^{20}Ne reaction down to the very low energy point of 186 keV. This measurement is extremely challenging on the surface of the Earth due to the presence of natural radioactivity. The experiment was done in the China Jinping Underground Laboratory (CJPL), which is currently the deepest underground laboratory. Zhang et al. reported a key resonance at 225 keV for ^{19}F(p,γ)^{20}Ne reaction rate, which is significantly higher than the previous experimental results, making this reaction a possible nuclear path to generate more calcium (Ca) through the breakout from the carbon–nitrogen–oxygen (CNO) cycle inside stars. With this new rate, Zhang et al. reproduced the Ca abundance in one of the oldest stars, SMSS0313-6708, whose Ca abundance is mysteriously higher than the expected value in such old stars. This study also shed light on solving the puzzles of discaccord between the observed abundance and theoretical computation from nuclear astrophysical experiments. Figure 1 shows an artist's impression that illustrates how the nuclear reaction experiment connects with distant stars.

It was realized that all the known elements were produced by either the Big Bang nucleosynthesis or stellar nucleosynthesis. The Big Bang nucleosynthesis created almost all the hydrogen (H) and helium (He) and a few light nuclides including lithium, beryllium, and boron. Then, stars take over,[2] and they synthesize elements all the way up to iron by nuclear fusion, with H and He as materials. Elements heavier than iron were produced via neutron capture processes inside stars or during violent explosions (eg, supernova) and merger events (eg, neutron stars merger).

With this "timeline," the universe enriches the elements by generations of stars, among which the first and second generations are evidently important.[3] The first-generation stars in our universe started shining $\sim$0.2 giga (10^9) years after the Big Bang. These stars, also known as population III stars, created "metals" (elements that are heavier than He are called metals in astronomy) via nuclear fusions and later spread their creations by deadly explosions into the interstellar medium, from which the second-generation stars were born. Given the short lifetime of the first-generation stars, they have long been dead. As a result, the oldest stars seen in our local universe today are second-generation stars, which were born in the ashes of the first generation. Spectroscopic observations of these oldest stars reveal the nature of their progenitors, ie, the chemical signatures of the early universe and the properties of the first supernovae.

The second-generation stars that still live today are all very old, with ages over $\sim$13 giga years. They carried only a few iron that were created by their progenitors and the succedent supernova explosion. Such stars attracted a wide range of attention from observational, computational, theoretical, and experimental (astro)physicists because the basic principle here is that the abundance of observations and calculations (within a certain theoretical frame and with experimental data as source input) should agree with each other. Otherwise, our understanding of an element's origin is bound to be somewhat problematic.

Unfortunately, such agreements cannot be always archived. One example is that the observed Ca abundances in the oldest stars were mysteriously higher than the computed value from stellar models. The ultra-metal-poor star SMSS0313-6708,[4] one of the oldest stars ever known, shows a [Ca/H] = -7 dex (here, [Ca/H] is defined as $\log[n(\mathrm{Ca})/n(\mathrm{H})]_{\mathrm{star}}/\log[n(\mathrm{Ca})/n(\mathrm{H})]_{\mathrm{Sun}}$, where n(Ca) and n(H) are number densities of Ca and H, respectively; a "dex" means an order of magnitude), while the predicted Ca abundance is up to $\sim$2 dex lower than the observation.

The inconsistency can be due to a number of reasons, but in most cases, astrophysicists tend to first suspect that it is caused by observation uncertainties or questionable theoretical calculations. This is easy to understand. On one hand, the oldest stars are distant and faint, which makes the observational uncertainties large. On the other hand, the computed abundances are model dependent, and inaccurate treatment or missing some complex physical processes could lead to biases.

The nuclear reaction rates are also a possible factor. However, confirming this could be very challenging. One important reason is that sometimes a big change in reaction rate will lead to only a tiny change of computed abundance, as the computation considers numerous processes and effects, thus diluting the impact of changing the reaction rates. However, if the reaction opens/strengthens a nuclear path that could affect the internal environment of a star (eg, temperature, radiation, convection), things could be different. The work from Zhang et al. is such a case. Zhang et al. managed to directly measure the cross-sections of ^{19}F(p,γ)^{20}Ne down to 186 keV, and they detect a resonance at 225 keV, which has a noticeable contribution to its reaction rate but was missed by previous studies. The new resonance discovered shows that the ratio of the reaction rates from two competing processes, ^{19}F(p,γ)^{20}Ne and ^{19}F(p,α)^{16}O, was 7.4 times larger than the previous measurement. The former reaction tends to break the CNO cycle and generate more ^{20}Ne (therefore more Ca), while the latter reaction tends to generate more ^{16}O and keep the CNO cycle running (therefore less Ca). With this new reaction rate, Zhang et al. reproduced the observed Ca abundance in SMSS0313-6708.

The direct measurement of the ^{19}F(p,γ)^{20}Ne reaction rate down to a very low energy point is extremely challenging on the surface of the Earth. This is because the strong 6.13 MeV γ-ray from competing channels will interfere with the measurement. Therefore, this experiment has to be carried out underground. The deep underground laboratory can greatly reduce the interference caused by cosmic rays and provide a measurement environment with an extremely low background, which is essential to the accurate measurement and research of rare reaction events.

The China Jinping Underground Laboratory[5] covers more than 2400 m below the peaks of the Jinping Mountains, currently ranking as the deepest laboratory in the world. The rocks above the laboratory block a large proportion of the natural radioactivity of the Earth's surface. The cosmic ray flux is about 100 times lower than that of the underground laboratory in Gran Sasso, Italy, another famous underground laboratory for nuclear reaction experiments. Eight new experimental spaces were built in CJPL for multidisciplinary deep scientific research. Among them, the A1 experimental space is used to host the Jinping Underground Nuclear Astrophysics experiment (JUNA) device. The JUNA has a 400 kV accelerator with the currently highest beam in underground laboratories of the world, providing world-class conditions for direct measurement of important nuclear astrophysics reactions in the energy range of 50–400 keV for proton-induced reactions and 50–800 keV for alpha-induced reactions.

Besides Ca abundance in the ultra-metal-poor stars, there are still numerous puzzles regarding the abundance inconsistency between observations and theoretical computations. This study shed lights on solving such puzzles from nuclear astrophysical experiments. It is for sure that CJPL and JUNA will continue to conduct challenging nuclear reaction experiments and provide new data for state-of-art nuclear astrophysical studies.

Figure 1. Nuclear physical experiment deeply underground provides clues of elements synthesis deeply inside ancient stars. The top part shows various stars with a background of the Milky Way, while the bottom part shows the CJPL, currently the deepest laboratory at 2400 m below the Earth's surface.

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DECLARATION OF INTERESTS

The authors declare no competing interests.