FEATURE

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Research Area: Experimental Physics

Supernova Explosions and Neutrinos

When and where were the elements created?

A variety of different elements exist around us. Human bodies contain oxygen, carbon, and hydrogen as their principal components. The main components of the Earth are believed to be iron, oxygen, silicon, and magnesium. Gold and silver are among those elements known as precious metals. Uranium is used in power reactors for generating electricity. When and where in the history of the universe were these elements created?

Recent high-sensitivity observations of the universe have shed light on how the universe began. The universe began in a fireball called the Big Bang 13.7 billion years ago. The fireball was a lump of energy that created particles and antiparticles (quarks and antiquarks, electrons and positrons, and so on). Through a certain mechanism, antiparticles disappeared and particles remained, and the elements were synthesized from quarks and electrons. Did the Big Bang synthesize the different kinds of elements around us? The universe has been expanding since the Big Bang. Nucleosynthesis at the Big Bang was a competing process with this expansion. Unfortunately, because the speed of expansion was very fast, only hydrogen, helium, and a tiny amount of lithium were created, and elements with heavier mass could not be formed.

Nuclear fusion reactions are needed to create heavier elements from hydrogen and helium. At the center of the Sun, nuclear fusion reactions do take place, but there the temperature is about

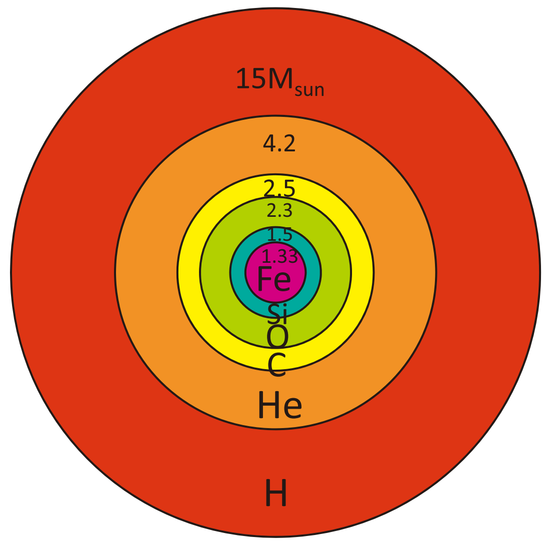

Figure 1: Inside a heavy star just before a supernova explosion.

10^7 degrees and the density is about 150 g/cm^3. Nuclear fusion reactions at these temperatures produce helium from hydrogen, and it is difficult to produce elements heavier than helium. Inside stars that are ten or more times heavier than the Sun, an environment with much higher temperatures and densities can be created. At a temperature as high as 10^8 degrees and a density as high as 10^4 g/cm^3, a nuclear fusion reaction of three helium atoms into a carbon atom takes place. At temperatures as high as 10^9 degrees and densities as high as 10^6 g/cm^3, it becomes possible to produce oxygen, neon, sodium, magnesium, etc. from nuclear fusion reactions of carbon nuclei. At still higher temperatures and densities, silicon is produced from oxygen, and iron, cobalt, nickel, and other elements are produced

Figure 2: The supernova explosion in the Large Magellanic Cloud in 1987. Photo: before (right) and after (left) the explosion.

from silicon. When a star reaches this point, it has the onion-like inner structure shown in Fig. 1: a core mainly comprising iron is formed at the center, and outward from the core are formed layers of silicon, oxygen, helium, and hydrogen. Nuclear fusion reactions cease at this point. This is because iron nuclei have the largest binding energy (this means that protons and neutrons are most densely packed in the iron nucleus), and therefore no further thermal nuclear fusion reactions are possible beyond iron. (Incidentally, nuclear fusion reactions proceed rapidly in these heavy stars. These onion-like structures are formed in about 10 million years. It can be seen that the lifetimes of these heavy stars are very short compared with the present age of our Sun, which is 4.6 billion years.) However, now the stellar core undergoes an interesting phenomenon. As energy flows out from the core, it shrinks, and its temperature increases. Above approximately 5×10^9 degrees, iron become unstable because of the endothermic reaction, which disintegrates the iron nucleus into helium nuclei ($^{56}Fe + \gamma \rightarrow 13\,^4He + 4n - 124.4$ MeV). Then, electron captures (referring to the neutronization of protons both inside and outside the nuclei: $e^- + p \rightarrow \nu_e + n$) occur in association with an increase in the density and emission of neutrinos. This leads to the formation of a neutron star (or black hole), which is a stellar object with a very high density (10^{14} g/cm^3) comparable to that of nuclei. Even the mass of the Sun is compactly packed within a size of about 10 km. This marks the beginning of a supernova explosion.* Since the potential energy of an object is inversely proportional to its size, tremendous energy is produced by the formation of this compact star. Part of the energy is used to

* Supernova explosions are classified using a spectrum of optical observations into the Ia-type (without a hydrogen line, but with a silicon line), the Ib-type (without a hydrogen line, but with a helium line), the Ic-type (without hydrogen, silicon, or helium lines), and II-type (with a hydrogen line). It is thought that the Ia-type supernovae are due to the explosive burning of carbon white dwarfs, while the Ib, Ic, and II-types are the result of the gravitational collapse of the central core.

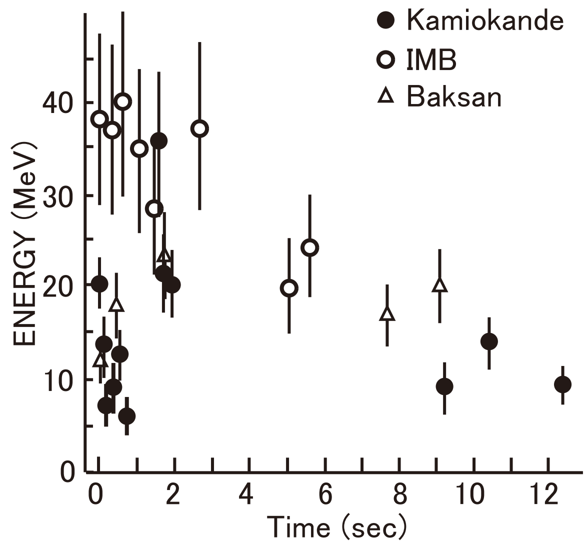

Figure 3: The neutrino events detected by the Kamiokande, IMB, and Baksan experiments.

produce a shockwave, which leads to the explosion of the star. The shockwave blows out the star's outer layers. This causes a very rapid increase in local temperatures and pressures, leading to very rapid nuclear reactions taking place in an extremely short period. Heavy elements such as gold, silver, and uranium are synthesized through these nuclear reactions. Supernova explosions disperse the elements inside the star out into space. These dispersed elements begin to coalesce due to gravity, leading to the birth of new stellar objects. Both the Sun and the Earth were formed as a result of these processes.

The above scenario is depicted on the basis of astrophysics and nuclear physics, and its verification required observation of a supernova explosion. I will discuss these observations next.

Observing supernova neutrinos

The energy released from a supernova explosion, which is the source of various kinds of elements, is estimated to be more than 10^{46} joules. This is equivalent to several hundred times the total energy radiated from the Sun since its birth, showing just how enormous it is. Neutrinos carry almost all (about 99%) of this energy out of the star. This is because they interact weakly with matter, and therefore they can pass through the high-density inner layers of the star. In 1987, an event occurred that verified the scenario of the supernova explosion.

On February 23, 1987, the Kamiokande experiment and the Irvine-Michigan-Brookhaven (IMB) experiment detected a neutrino burst associated with Supernova SN1987A. Kamiokande was a detector built in 1983, located in the town of Kamioka, Gifu Prefecture in Japan, 1000 m underground in the Kamioka mine. It was a 3,000-ton water tank equipped with 948 photomultipliers, each 50 cm in diameter. The IMB experiment had a 7,000-ton detector built 600 m underground in the Morton salt mine in Ohio, USA. It featured 2,048 photomultipliers, each 20 cm in diameter. This supernova explosion occurred in the Large Magellanic Cloud, 170,000 light years away. Fig. 2 shows the optical observation of SN1987A.

Fig. 3 shows the neutrino events detected by the Kamiokande, IMB, and Baksan experiments. (This last experiment reported the observation at a later date.) Kamiokande, IMB, and Baksan observed eleven, eight, and five neutrinos, respectively. As can be seen from the range of the horizontal axis, neutrinos

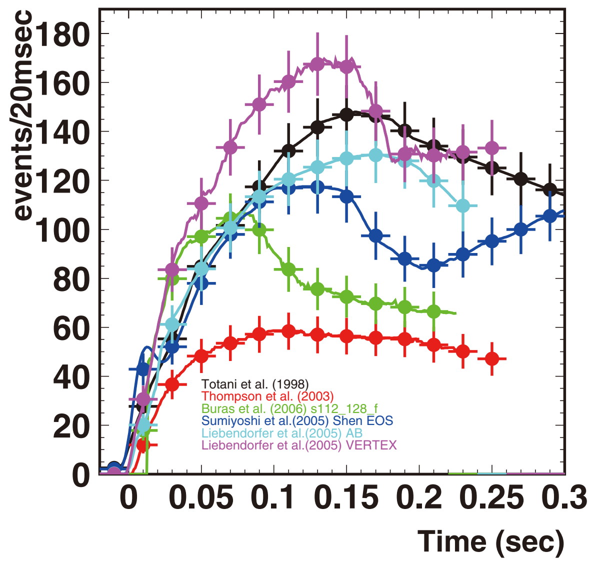

Figure 4: The event rates at Super-Kamiokande are predicted by several simulations of the supernova explosion. They are plotted as a function of time up to 0.3 seconds after explosion. The distance to the supernova is assumed to be that to the galactic center (approx. 33,000 light years).

were emitted in only 10 seconds. This means that the central core collapses gravitationally in only about 10 seconds. In contrast, it takes several hours for light to arrive outside the star, having to wait until the outer layers of the star are blown out by the shock waves generated by the explosion. In fact, it was about three hours after the neutrino emission that the increase in the luminosity of SN1987A was observed.

Although only 24 neutrino events in total were observed by Kamiokande, IMB, and Baksan, the energy released from the supernova explosion was estimated from the number of events and their energies. It was nearly consistent with the expected value (approx. 3×10^{46} joules).

Future observations and investigation of the explosion mechanism

Although the observations of neutrinos from SN1987A showed the validity of the basic scenario of the supernova explosion, the detailed mechanism of the explosion is not yet clear. Several groups around the world are trying to explode supernovae in computer simulations. As yet, they have not been successful with exploding stars, though their input information is accurate. It seems that the present simulations are missing some physical processes. To solve these problems, it is necessary to examine the explosions more closely by detecting many more supernova neutrinos. If a supernova explosion occurs in our galaxy, the 50,000-ton detector Super-Kamiokande (SK) would detect nearly 10,000 events. Fig. 4 shows the event rate in SK, predicted by several simulations, as a function of time up to 0.3 seconds after the explosion. The distance to the supernova is assumed to be that to the galactic center (about 33,000 light years). The observation of a precise time profile would make it possible to identify which explosion model is correct.

High-density states formed in the supernova explosion may provide new insights into elementary particle physics. Although underground neutrino observations have clarified neutrino oscillations, a number of problems remain to be clarified: the third oscillation mode, hierarchical structure of the neutrino masses, and others. In the high-density core, it may be possible that neutrinos appreciably oscillate because of the effects of neutrino oscillations in matter (MSW effects), even though the mixing angles are small. So, it might be possible for the unknown oscillation parameters to be determined using the spectrum of the supernova

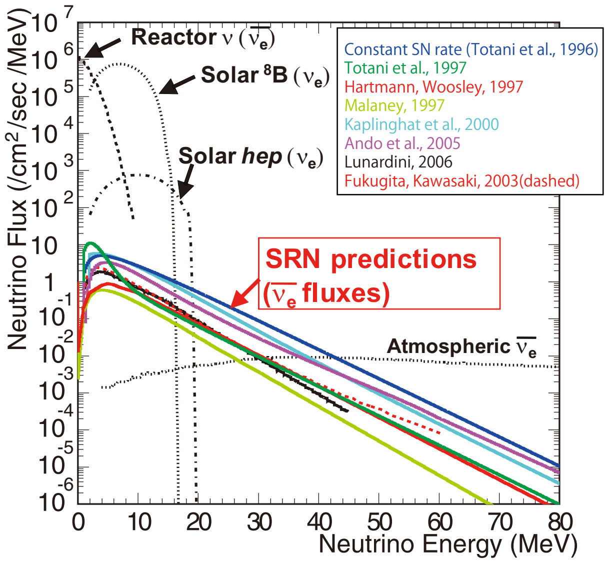

Figure 5: Energy spectra of various neutrinos striking the Earth's surface. The colored curves show the SRN spectra predicted by various models.

neutrinos.

It is said that supernova explosions occur in our galaxy once every 30 to 50 years. We are hoping that an explosion will occur in the near future, to provide us with a rich source of information.

Probing the history of the universe with supernova neutrinos

There are about 10^9 galaxies in our universe. Each galaxy has about 10^{11} stars. Since about 0.3% of the stars have masses larger than ten times the mass of our Sun, it is estimated that 10^{17} supernova explosions have occurred throughout the history of the universe. This means that, on average, one supernova explosion occurs every second somewhere in the universe. The neutrinos produced in the supernova explosions since the beginning of the universe are called supernova relic neutrinos (SRN). They must fill the present universe and their flux is estimated to be a few times 10 cm^2/sec. If we can detect these neutrinos, it may be possible to explore the history of how heavy elements have been synthesized since the beginning of the universe.

Fig. 5 shows the kinds of neutrinos arriving at the Earth's surface. The colored curves are the SRN spectra predicted by various models. On the lower energy side there are neutrinos from power reactors and neutrinos from the Sun, and on the higher energy side there are neutrinos which are produced by cosmic rays in the atmosphere. However, around 20 MeV, the SRN are believed to represent the main component. Note that solar neutrinos are particle neutrinos, while other neutrinos are electron antineutrinos. Consequently, if we can detect electron antineutrinos, we can see SRN in a range of approximately 10 – 30 MeV. We have begun the R&D necessary to enable SRN to be observed in Super-Kamiokande. Specifically, a material called gadolinium is dissolved (0.1% by mass) in a water tank, with the object of detecting electron antineutrinos with positrons and gamma rays as signatures. From the reaction of an electron antineutrino on a proton, a positron and a neutron are produced, and gamma rays are emitted from the subsequent capture of the neutron by gadolinium. We are now at the testing stage, but once the experiment gets fully underway, a few signal events should be detected every year. Supernova neutrinos should provide us with a new way of looking at the universe.