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Three-dimensional nuclear chart - Understanding of nuclear physics and nucleosynthesis in stars -

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Abstract. Three-dimensional (3D) nuclear charts were created by using toy blocks, which represent the atomic masses per nucleon number and the total half-lives for each nucleus in the entire region of the nuclear mass. The bulk properties of the nuclei can be easily understood by using these charts. Consequently, these charts have been used in outreach activities for the general public and high school students. As an example, an application for a lecture of nucleosynthesis in stars is introduced, and some explanations for the abundance of iron, the origin of uranium, etc., on planet Earth are given with the 3D chart.

1. Introduction

All the materials found on planet Earth are made of atoms, and each atom is composed of electrons and a nucleus. A nucleus is ten thousand times smaller than an atom and is composed of protons and neutrons. To represent the properties of various nuclei, nuclear physics researchers use a nuclide chart, which is a two-dimensional (2D) chart that shows the number of protons on the vertical axis and the number of neutrons on the horizontal axis. These kinds of charts have been published by institutes worldwide. Our institute, JAEA, has also published these charts, such as one shown in Figure 1, on a regular basis [1, 2]. By using this chart, users can obtain nuclear half-lives, nuclear decay modes, isotopic abundances, etc. However, such a chart is rather difficult to understand and is only used by experts.

Recently, we constructed two three-dimensional (3D) nuclear charts with toy blocks, which represent the atomic masses per nucleon number and the total half-lives for each nucleus in the entire region of the nuclear mass. These charts have been used in outreach activities for the general public and high school students.

2. Three-dimensional nuclear charts

According to Einstein's special relativity, the total energy, E, mass of matter, m, and light velocity, c, have the relation $E = mc^2$. That means, in the world of atomic nuclei, the mass itself is the total energy, and the mass governs the nuclear system as nuclear decays, nuclear reactions, etc. Figure 2 shows the first chart of the nuclides in 3D, in which the height of each block indicates the nuclear mass‡ per nucleon. In this case, for example, one height corresponds to 100 kilo-electron volts per c^2. In the lower-left region of the chart are lighter-colored blocks, which are the nuclei with a smaller number of protons and neutrons, such as hydrogen and helium. In the upper-right region are darker-colored blocks, which are the heavier nuclei, such as gold and uranium. The masses are larger at both ends of the chart, and the lowest mass per nucleon is that of iron-56 (^{56}Fe. The number 56 is the mass number, which is the total number of neutrons and protons), represented by the white block in Figure 2. The first ionization potentials of atoms are also represented on the left side. In most cases, the audience viewing these charts is not familiar with nuclear physics, and therefore a lecture begins with the ionization potentials of atoms to introduce the idea of the closed shell structure of a rare gas being 2 for helium, 10 for neon, 18 for argon, 36 for krypton, 54 for xenon, 86 for radon, as evidence of the existence of periodicity. After that introduction, the closed shell structure of protons (8, 20, 50, 82, 114 (prediction) and 126 (prediction) on

‡ Strictly, nuclear mass is the excess mass of the atoms. The atomic mass excess for a given number of protons Z and neutrons N of a nucleus is defined as $m_{\rm exc} = m_{\rm atom} - (Zm_{\rm H} + Nm_{\rm n}) - B_{\rm electron}$, where $m_{\rm H}$ is the mass of a neutral hydrogen atom, $m_{\rm n}$ is that of a neutron, and $B_{\rm electron}$ is the binding energy of electrons. The majority of an atom's weight is that of the nucleus. In nuclear studies, neutrally charged atomic masses are discussed instead of an atom's nuclear mass.

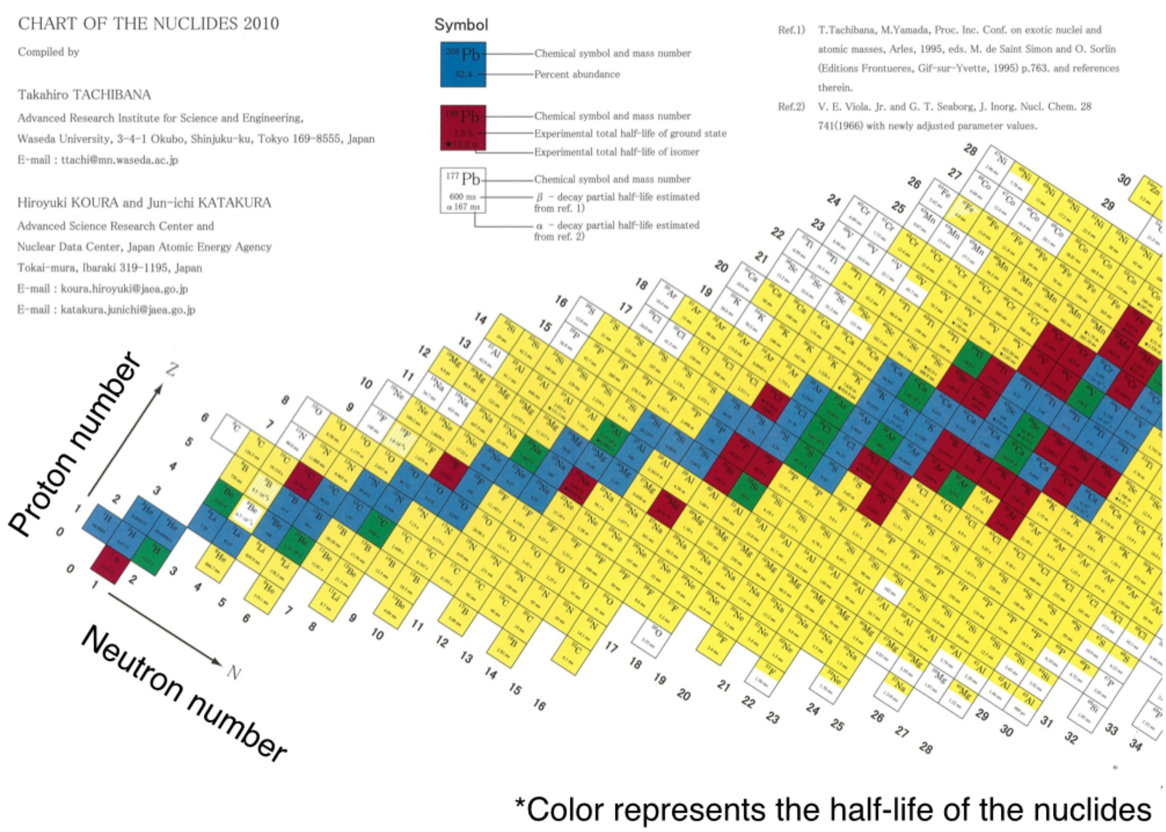

Figure 1. A 2D chart of the half-lives of nuclides against neutron number and proton number from Ref. [2]. The color represents the half-life: Yellow: shorter than 10 minutes. Red: longer than 10 minutes and shorter than 30 days. Green: longer than 30 days and shorter than $5{\times}10^8$ years. Blue: longer than $5{\times}10^8$ years. (Stable). White: Unidentified nuclei (Values are obtained from predictions [3]).

the vertical axis) and neutrons (8, 20, 50, 82, 126 and 184 (prediction) on the horizontal axis) is introduced.

Figure 3 shows the second 3D chart of the nuclides. In this chart, the heights of the blocks represent the half-lives of the nuclei. The stable nuclei are shown as black pillars in a bending line from the lighter to the heavier region, up to lead-208 (^{208}Pb) and bismuth-209 (^{209}Bi). The successive order of stable isotopes terminates at ^{208}Pb and ^{209}Bi. The suppression due to α decay is found in the heavier region and not in the successive stable region, then an isolated region with long-lived isotopes continues. The isolated region includes actinides such as thorium and uranium. Note that the half-lives of thorium-232 (^{232}Th) (1.4×10^{10} years) and uranium-235 and 238 (^{235,258}U) ($7.0{\times}10^8$ years, $4.5{\times}10^9$ years) are much longer than a human lifespan; however, they are very short in comparison with other (lighter) stable isotopes.

3. Using the 3D Chart

The bulk properties of the nuclei can be easily understood by using these charts. Therefore, these charts have been used in high school lectures to describe nucleosynthesis in the universe.

In the universe, many types of elements, such as gold, iron, carbon, and uranium, exist. But why do these elements exist in the universe? The key to solving this question is in the evolution of the stars throughout cosmic history. For 13.8 billion years, the universe has created various types of elements, and the nuclear bulk properties, as visualized in Figures 2 and 3, play an important role in the synthesis of elements. We

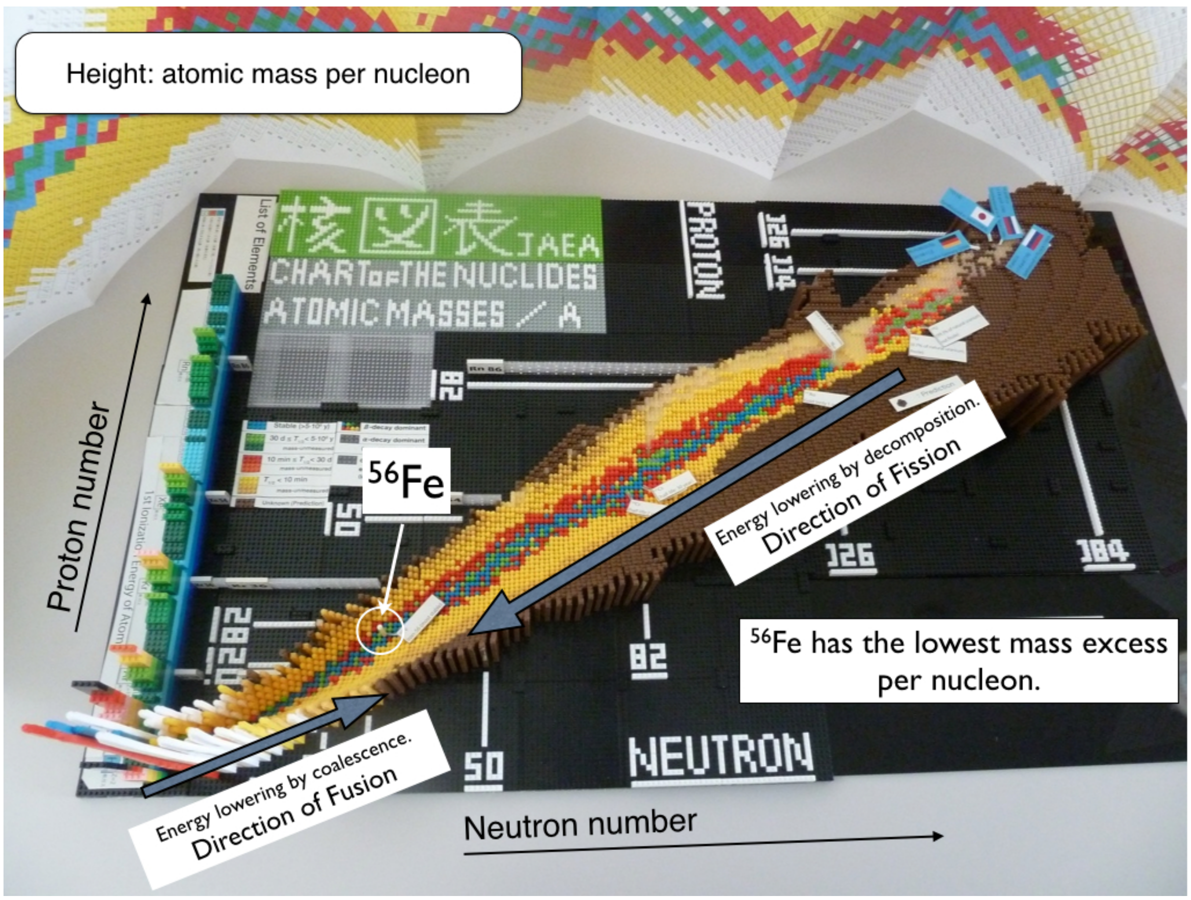

Figure 2. A 3D chart of the atomic masses of nuclides against neutron number and proton number. The size is 96 (width)×56 (depth)×30 (maximum height) cm. Brown-colored blocks: nuclei theoretically predicted by the author (∼3,500 nuclei) [8]. Other blocks: experimentally identified nuclei (∼3,000 nuclei) [2, 4, 5, 6]. The colors other than brown classify the half-lives as in Fig. 1. The mass values of experiments and predictions are obtained from Refs. [7] and [8], respectively. The first ionization potentials of atoms from hydrogen to rutherfordium (atomic number 104) are also shown on the left side of the chart. The Japanese character set appears on the left side of "JAEA" in the green panel on the upper side of the chart. The Japanese characters mean "chart of the nuclides" as shown in English in the clear panel directly below the green panel.

investigated the ability of non-experts to understand the world of nuclear physics and the history of the genesis of elements by using these charts.

In our lecture, we give a narration in the following scenario:

(i) **Big bang nucleosynthesis**: The early universe created light elements from protons, (the nucleus of hydrogen) namely hydrogen-1 and 2 (^{1,2}H), helium-3 and 4 (^{3,4}He) and lithium-6 and 7 (^{6,7}Li). Heavier isotopes could not be created due to the barrier of the very short life of beryllium-8 (^{8}Be), which is 6.7×10^{-17} s, which has a mass number of 8.

(ii) **Normal nucleosynthesis in a star**: After the first star appearance (∼0.2 billion years after the big bang), stars could create light isotopes. Firstly stars created ^{4}He from protons. If the three α particles (nuclei of ^{4}He) were concentrated in a dense and rather high-temperature situation, they made carbon-12 (^{12}C): this is known as the triple-α reaction. By overcoming the ^{8}Be barrier, stars could make heavier isotopes up to iron-56 and its neighboring isotopes. In the 3D chart, the direction of the process is expressed as the slope from hydrogen to the basin, where iron is at the center, as shown in Fig. 2. By going down the slope, nuclei gain energy from the difference of the nuclear masses and the resulting nuclei release the energy: this is nuclear fusion. Stars approximately 8 times higher in mass than the sun can be assumed to attain the creation of iron: the sun is supposed to have created elements

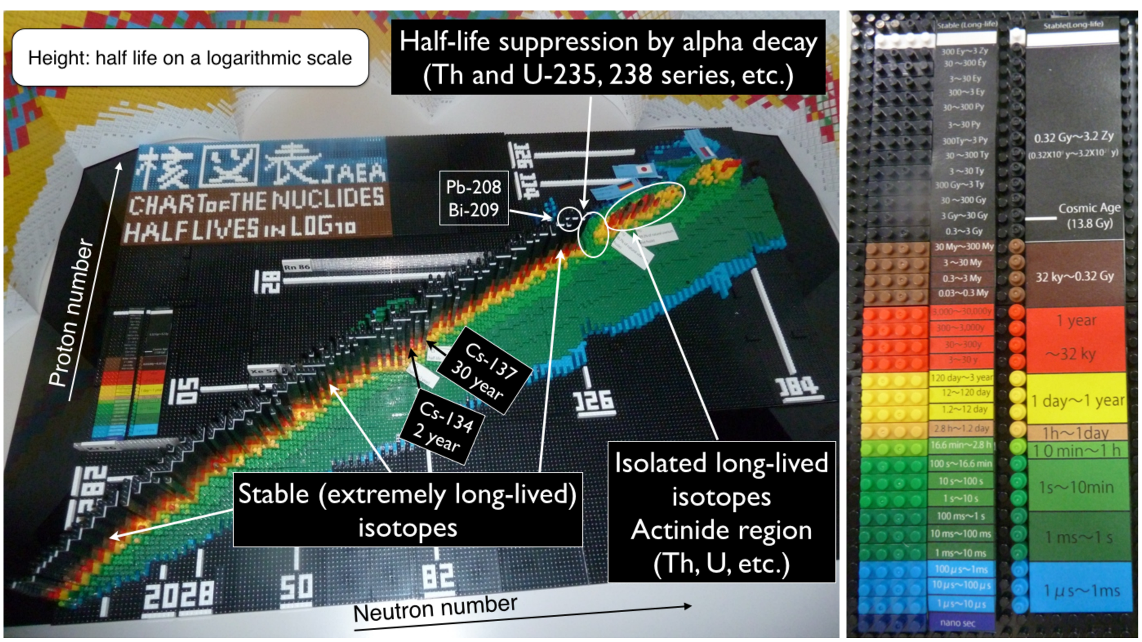

Figure 3. A 3D chart of the half-lives of the nuclei of nuclides, where one height corresponds to ten times the half-life on the logarithmic scale. Both experimental [2] and theoretical half-lives [3] are adopted. The relation between half-life and color is shown in the legend (right). The heights of the white blocks sandwiched between black blocks represents the infinity of the half-lives. The half-lives represented as black blocks above the white blocks are regarded as infinite.

up to carbon and oxygen, but not iron due to its lighter weight.

(iii) **Slow neutron-capture process (s-process)**: Based only on the consideration of energy gain, stars can only create at most iron and its neighboring nuclei. To understand the existence of heavier isotopes such as gold and lead, a non-equilibrium reaction process is required. If neutrons are abundant in a star, the nuclei can absorb neutrons easily due to their neutral charge, and the synthesis proceeds to heavier nuclei. This is the idea of the slow neutron capture process (s-process). The asymptotic giant branch (AGB) star, a type of the red giant branch (RGB) star, occurs in a late phase of stellar evolution and is a candidate site to enable such a condition. In AGB stars, stable nuclei (the blue blocks in Figure 2 and also the black blocks in Figure 3) capture neutrons via β^- decay one by one forming heavier nuclei up to ^{208}Pb and ^{209}Bi. The duration time is in the order of thousands of years. The s-process may be considered as a non-equilibrium process, and therefore the s-process nuclei may be physically considered to be "unstable". The half-lives of the "unstable" nuclei, however, are extremely long. In the case of ^{209}Bi, for example, its half-life is measured as 1.9×10^{19} years [9]. This value can be also confirmed in the 3D chart (half-life version) in Figure 3.

(iv) **Rapid neutron-capture process (r-process)**: In the s-process, synthesis reaches up to ^{208}Pb and ^{209}Bi. However, we have even heavier isotopes such as thorium and uranium on planet Earth, and we use these isotopes as atomic energy. These isotopes are created by the much more "rapid" neutron capture process, called the r-process. The neutron flux in this process is estimated to be $10^{22}/(\mathrm{cm}^2\cdot\mathrm{sec})$, which is much denser compared with the s-process, $10^{5-10}/(\mathrm{cm}^2\cdot\mathrm{sec})$. A candidate site of this process is a supernova explosion. A neutron star merger is also another probable candidate. In these cases, the r-process creates very neutron-rich, heavier nuclei, as shown in the brown-colored region in Figure 2. The duration time is in the order of one to ten seconds. Then the reaction process reaches the much heavier neutron-rich nuclear mass region that includes uranium and is where β^- decay occurs, and reaches stable actinides such as ^{232}Th and ^{235,238}U. In the current understanding, uranium creation is supposed to be performed only under the r-process of nucleosynthesis.

The solar system abundances of isotopes [10] are constructed as a 3D chart in Figure 4. This construction is also expressed as a function of the number of protons and neutrons. As can be seen, ^{1}H is the most abundant all of the isotopes and ^{4}He is the second most abundant. Their percentages are approximately 90 % and 10 %, respectively. The other isotopes are quite small in abundance, although there is some structure. The less abundant isotopes are in the ^{8}Be region (see (i)). A dominant abundant region is found in the ^{56}Fe region in comparison with neighboring nuclei (see (ii) and Figure 2) and a successively decreasing region is found up to ^{208}Pb and ^{209}Bi (see (iii)). The isolated region includes ^{232}Th and ^{235,258}U (see (iv) and Figure 3).

4. Actual activities

Using our charts, a lecture entitled "Alchemy of the Universe" was given to the general public and to a high school science class in Japan as follows:

- General public at the Science Cafe during the 2013 science and technology week (Apr. 16, 2013, Chiyoda-ku, Tokyo (Information plaza in Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan)), 29 people, 90 min.
- High school students at a science school in Fukushima high school in Fukushima prefecture (approved as a "super science high school" by MEXT) (Aug. 23, 2013), ∼50 students, 90 min.

The audiences seemed to enjoy the lectures and responded to them very well. This may have been due to the use of the colorful charts constructed with toy blocks. Furthermore, the audiences seemed to enjoy the narration in which the universe was depicted as a large planet and the nucleus as a small planet to describe the origin of elements of our world.

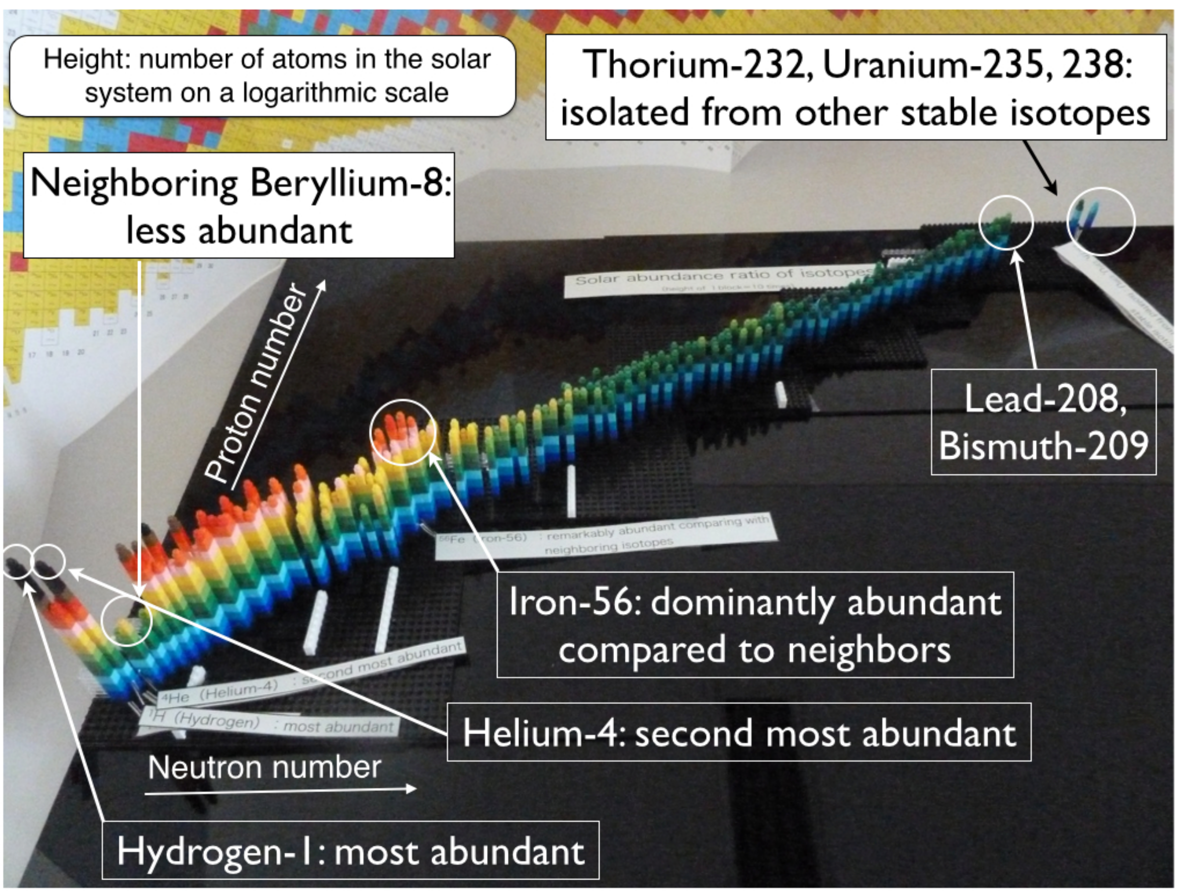

Figure 4. Relative abundances in the solar system in 3D. The height represents the number of atoms on the logarithmic scale. Data are taken from Ref. [10].

We constructed two total sets of the 3D charts (mass and half-life versions). These charts are composed of several parts and can be separated into each part to transport to other places more easily. As the next step, we will try to distribute this chart to schools and public places. Some of the staff at the high schools in Fukushima and Ibaraki prefectures in Japan have expressed interested in recreating our 3D charts. Among them, for example, is a class at Shinchi high school in Fukushima prefecture, which has already started to recreate one of our 3D charts (the lighter part of the chart including iron isotopes has already been finished).

5. Conclusion

In this study 3D nuclear charts were constructed using toy blocks, which represent the atomic masses per nucleon number and the total half-lives for each nucleus in the entire region of nuclear mass. The bulk properties of the nuclei can be easily understood by using these charts. These charts have been used in outreach activities for the general public and high school students. As an example, a lecture about nucleosynthesis in stars was given, as well as some explanations using the 3D chart for the abundance of iron and the origin of uranium, etc., on planet Earth.

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