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Cosmic clock and thermometer for neutrino process

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We suggest a ^{138}La - ^{138}Ce - ^{136}Ce system as a new nuclear cosmic clock for measuring the time elapsed from a single neutrino process episode to the present. This clock is applied to meteoritic samples produced mainly by a single nucleosynthesis episode. The nuclear structure of ^{138}La is crucial for the performance of this clock and its astrophysical origin. The lowest 1^+ state in ^{138}La has not been established experimentally. If this state is a β unstable isomer, ^{138}La should be destroyed in the ν-process and the clock cannot work well. However, this system can be used as a new cosmic thermometer. To study the nuclear structure of ^{138}La, we perform a shell model calculation. Our shell model calculation shows the 1^+ state may be stable against the β decay and our proposed clock can perform.

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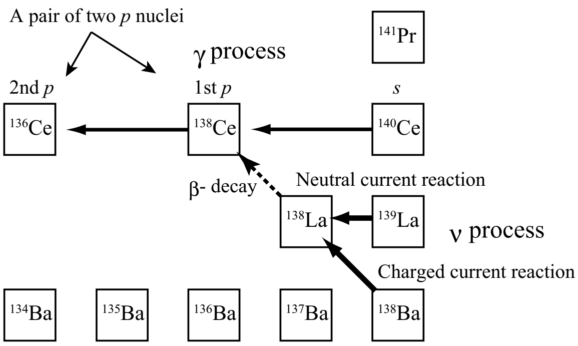

Figure 1: A partial nuclear chart around La and nucleosynthesis processes.

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1. Introduction

Long-lived radioactivities are used as the cosmic clocks but only six clocks with their half-lives of 1 $\sim$ 100 Gyr are known. They are ^{40}K [1], ^{87}Rb [2] and ^{176}Lu [3, 4] for the *s*-process or explosive nucleosynthesis in supernovae (SNe), and ^{187}Re [2, 5, 6], ^{232}Th [1] and ^{238}U [1] for the *r*-process. However, the long-lived cosmic clock for the neutrino reaction nucleosynthesis in supernovae (ν-process) has not been proposed.

The ν-process was proposed as origin of some rare isotopes of heavy elements and light elements [7]. An isotope ^{138}La is a key to understand the ν-process [7, 8, 9, 10, 11, 12] because only two isotopes, ^{138}La and ^{180}Ta, among the heavy elements are considered to be mainly synthesized by the ν-process [7, 9] but ^{180}Ta is also considered to be produced by the *s* process [13] or the *p*-process (γ-process) [14]. A contribution of a charged current reaction to ^{138}La was quantitatively calculated [8]. Recently, a result that about 90% in the solar abundance of ^{138}La can be explained by the ν-process was reported [9]. However, the origin of ^{138}La has not been established by astronomical observations or analyses of meteorites. We propose a new nuclear cosmic clock for the nucleosynthesis process of ^{138}La and to present a shell model calculation result of the nuclear structure of ^{138}La, which is of importance to the performance of the clock.

2. Proposal of a new cosmic clock for the ν-process

The nucleus ^{138}La decays to ^{138}Ce or ^{138}Ba with a half-life of 10.1×10^{10} yr. Here we suggest a ^{138}La - ^{138}Ce - ^{136}Ce system as a new cosmic clock for the ν-process. This clock is applied to meteoritic samples whose compositions were mainly produced by a single nucleosynthesis episode. The pre-existing *p*-nuclei including the three nuclei almost disappear by the weak *s*-process in an evolutionary state of massive stars. The three nuclei are synthesized in different layers in the SN explosion. The meteoritic compositions are produced after the mixing of the materials originated from the different layers. Thus a single meteoritic sample may include the three isotopes. Since the manner of the mixing in individual meteorites is different, the estimation of the initial abundance of ^{138}Ce is difficult.

In our proposed system the initial γ-process abundance of ^{138}Ce can be calculated by an empirical scaling law between two *p*-nuclei with the same atomic number, which was found in the solar system abundances [4]. There are nine such pairs in nature. As shown in Fig. 1, the first and

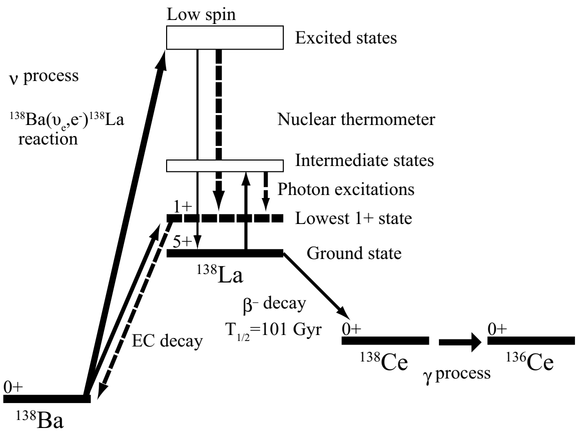

Figure 2: A schematic view for the synthesis and destroy of ^{138}La in the ν-process

second p-nuclei are lighter than the s-nucleus by two and four neutrons, respectively. We found the empirical scaling law that the abundance ratios of N(1st p)/N(2nd p) is almost constant in a wide region of atomic number, where N is the solar abundance [4]. This empirical law leads to "the universality of the γ-process" that the scaling holds for nuclei produced in individual SNe [4, 15].

If the abundances of ^{136,138}Ce and ^{138}La in a single sample produced mainly by a single supernova are measured, the time elapsed from a ν-process episode, T, can be calculated by

$$T = -\frac{T_{1/2}(^{138}\text{La})}{ln2} \times$$
$$ln\left(\frac{N(^{138}\text{La})}{N(^{138}\text{La}) + \frac{1}{b}\Big(N(^{138}\text{Ce}) - R_{pp}(\text{Ce}) \times N(^{136}\text{Ce})\Big)}\right), \qquad (2.1)$$

where N is the observed abundance in the sample, R_{pp} is the initial N(1st p)/N(2nd p) ratio at the freezeout of the γ-process, and b is the branching ratio of the β^- decay of ^{138}La: $\lambda(\beta^-)$ / ($\lambda(\beta^-)$+λ(EC)). The R_{pp}(Ce) ratio can be estimated by γ-process theoretical calculations or the empirical scaling [4, 15]. The isotopic fractions of two elements of La and Ti in individual Al-Ca-rich inclusions were measured [16]. Recent studies of the meteorites show that we can expect that the samples of which ^{138}La is enhanced will be found.

3. Effect of the nuclear structure of ^{138}La

The nuclear structure of ^{138}La is crucial for its nucleosynthesis and the performance of our proposed clock. The nucleus ^{138}La (N=81) is lighter than ^{140}Pr (N=81) by two protons and these two nuclei locate near a neutron magic number of N=82. A fact that the ground state of ^{140}Pr is J^π=1^+ suggests that the 1^+ state may exist at a low excitation energy in ^{138}La. The lowest 1^+ state in ^{138}La has not been established experimentally. If the 1^+ state appear at low excitation energy, it may be a β unstable isomer since β decay from the 1^+ state can compete with an internal $E4$ transition to the 5^+ ground state. Our proposed clock cannot work well since the synthesized ^{138}La is destroyed via the β-decay of the 1^+ isomer populated by (γ,γ') reactions through intermediate states, but this system can be used as a cosmic thermometer like the ^{176}Lu thermometer [17].

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We calculate the nuclear structure of ^{138}La and ^{140}Pr in a shell-model. In a mass region around ^{138}La, the last proton can occupy either $d_{5/2}$ or $g_{7/2}$ orbit around the Fermi surface. The last neutron can occupy the $d_{3/2}$ orbit: namely, a hole of $d_{3/2}$ of a N=82 magic core. The 1^+ and 5^+ states in these nuclei can be understood by $(\pi d_{5/2})\otimes(\nu d_{3/2})^{-1}$ and $(\pi g_{7/2})\otimes(\nu d_{3/2})^{-1}$ configurations, respectively. We would like to stress that the observed 1^+ ground state of ^{140}Pr can not be understood by a simple shell-model picture because a coupling between a proton particle and a neutron hole cannot lead to the ground state with J^π=1^+ [18].

In our calculation, we take all orbits in the $Z,N = 50-82$ major shell, restricting excitation from $(\pi g_{7/2}d_{5/2})$ to $(\pi h_{11/2}s_{1/2}d_{3/2})$ up to 3 protons, and the proton seniority to $v \leq 3$. The effective Hamiltonian has the following form,

$$H = H_\pi + H_\nu + V_{\pi\nu}\,;$$
$$H_\pi = \sum_j \varepsilon_j^{(\pi)}\hat{N}_j^{(\pi)} + V_{\pi\pi}\,, \quad H_\nu = \sum_j \varepsilon_j^{(\nu)}\hat{N}_j^{(\nu)}\,, \tag{3.1}$$

where $\hat{N}_j^{(\pi)}$ ($\hat{N}_j^{(\nu)}$) represents the proton (neutron-hole) number operator on the orbit j. A surface-delta form (Yukawa form) is adopted for the proton-proton interaction $V_{\pi\pi}$ (the proton-neutron interaction $V_{\pi\nu}$). The single-particle energies $\varepsilon_j^{(\pi,\nu)}$ are determined from low-lying energy levels of neighboring $N = 81,82$ nuclei. As shown in Fig. 3, we successfully describe the observed excited states [19] lower than 500 keV and, in particular, the ground state spin of ^{140}Pr. We find that the coupling of two- and four-particle excited configurations of $\pi(g_{7/2})^{-2}(d_{5/2})^3$ and $\pi(g_{7/2})^{-4}(d_{5/2})^5$ leads to the 1^+ ground state.

Next, we apply this shell-model calculation to ^{138}La. As shown in Fig. 3, the calculated levels are consistent with the observed ones [20, 18]. It is noted that the 1^+ state locates at a low excitation energy as low as 169 keV. This energy is lower than the previously calculated energy $\sim$ 250 keV [18] because we use the extended interactions and larger space. This result suggests that the lowest 1^+ state may be stable against the β decay.

4. Summary

We suggest a ^{138}La - ^{138}Ce - ^{136}Ce system as a new nuclear cosmic clock for measuring the passing time from a single ν-process episode. This clock is used in analyses of primitive meteorites, which compositions were mainly produced by a single supernova. A 1^+ state should exist at a low excitation energy in ^{138}La. If the 1^+ state is an isomer, our proposed clock does not work well. We study the nuclear structure of ^{138}La and ^{140}Pr in shell model calcualtions. We reproduce the ground state of ^{140}Pr state including a coupling of two and four particle excitation states from $g_{7/2}$ to $d_{5/2}$. The calculated result shows that the 1^+ state in ^{138}La may be stable against the β decay.

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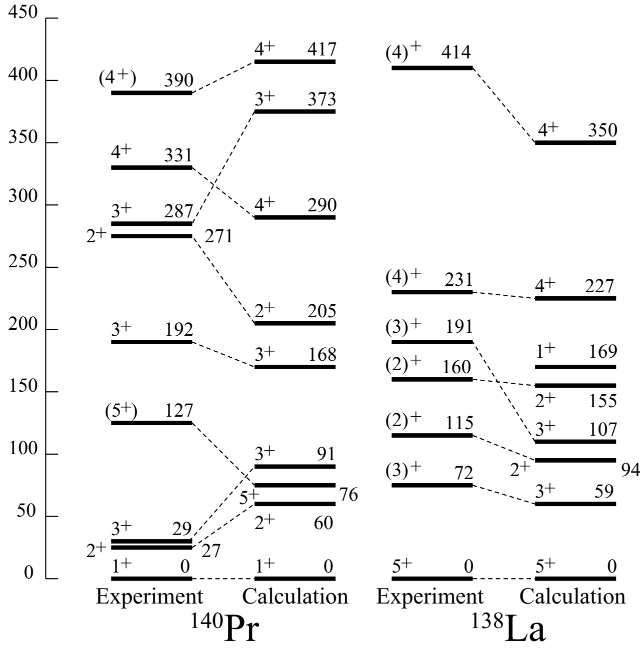

Figure 3: Calculated and observed level schemes of ^{138}La and ^{140}Pr.

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