Comment on "\(^{138}\text{La}-^{138}\text{Ce}-^{136}\text{Ce} \) nuclear cosmochronometer of the supernova neutrino process"

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Abstract

The nuclear chosmochronometer suggested by Hayakawa et al. [Phys. Rev. C \textbf{77}, 065802 (2008)] based on the \(^{138}\text{La}-^{138}\text{Ce}-^{136}\text{Ce} \) abundance ratio in presolar grains would be affected by the existence of a hitherto unknown low-energy \(1^+\) state in \(^{138}\text{La}\). Results of a recent high-resolution study of the \(^{138}\text{Ba}(^{3}\text{He},t) \) reaction under kinematics selectively populating \(1^+\) states in \(^{138}\text{La}\) through Gamow-Teller transitions provides strong evidence against the existence of such a hypothetical state.

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Hayakawa et al. proposed a new cosmochronometer based on the \(^{138}\text{La}-^{138}\text{Ce}-^{136}\text{Ce}\) abundance ratios in presolar grains. It utilizes the different dominant production mechanisms of \(^{138}\text{La}\) and \(^{136,138}\text{Ce}\): while all result from explosive nucleosynthesis in type II supernovae, the former nuclide is a product of the \(\nu\) process through charged-current reactions \(^2,^3,^4\) while the latter nuclides are synthesized in the \(p\) process \(^5\). One possible pitfall for the scheme (and also for the \(\nu\) process origin of \(^{138}\text{La}\)) would be the existence of a low-lying \(^1+\) state in \(^{138}\text{La}\) allowing electron capture (EC) decay to the stable \(^{138}\text{Ba}\) competing with the highly hindered \(\gamma\) decay to the \(^5+\) ground state. In fact, the final sentence of the paper reads "We present that the energy of the lowest \(^1+\) state may affect the chronometer performance and the \(\nu\) process origin of \(^{138}\text{La}\), and its measurement is desired." It is the purpose of this comment to report on recent experiments which allow to constrain the existence of such an EC branch.

The problem discussed in \(^1\) would be a \(^1+\) state in \(^{138}\text{La}\) with an excitation energy below the presently known \(^6\) lowest excited state \((E_x = 72\ \text{keV}, \ J^\pi = 2^+\)\). Such a state could be populated in the \((\nu_e, e)\) reaction either directly or by population of higher-lying \(^1+\) states and subsequent \(\gamma\) decay, since Gamow-Teller (GT) transitions are expected to dominate the reaction cross section \(^3\). For such a level EC decay to the \(^{138}\text{Ba}\) ground state (g.s.) could be competitive with \(\gamma\) decay because of the large transition multipolarity \((E4)\) of the latter. In principle, also \(\beta^-\) decay to the g.s. of \(^{138}\text{Ce}\) is possible. However, the smaller \(Q\)-value limits its branching ratio to a few percent of the EC decay.

Recently, we have performed a study of the \(^{138}\text{Ba}(^3\text{He},t)^{138}\text{La}\) reaction at the Research Center for Nuclear Physics, Osaka, Japan, at an incident energy of 140 MeV/nucleon and under a scattering angle of \(0^\circ\) \(^7\). A brief account of the work was given in \(^4\). Such experiments can be performed with excellent energy resolution reaching values \(\Delta E/E \simeq 10^{-5}\) in heavy nuclei \(^8\). At angles close to \(0^\circ\) this reaction selectively excites GT transitions. It is thus a spectroscopic tool to investigate \(^1+\) states in \(^{138}\text{La}\). Furthermore, GT matrix elements can be extracted from the data utilizing the procedures discussed in \(^9\) and \(^10\), respectively. These permit to estimate the EC lifetimes of a possible back decay to \(^{138}\text{Ba}\).

A spectrum of the reaction is shown in the upper part of Fig. \(^\text{2}\) taken from Ref. \(^4\). Since the \(^{138}\text{Ba}\) target material was embedded in polyvinylalcohol (PVA), a background line from the \(^{18}\text{O}(^3\text{He},t)^{18}\text{F}\) reaction is visible close to the expected g.s. energy of \(^{138}\text{La}\). The contribution of the PVA was subtracted by a measurement on a pure PVA target under
FIG. 1: Top: Spectrum of the $^{138}\text{Ba}(^{3}\text{He},t)^{138}\text{La}$ reaction at $E_{0} = 420$ MeV and $\Theta = 0^\circ - 0.5^\circ$, taken from Ref. [4]. The target consisted of $^{138}\text{BaCO}_3$ dissolved in PVA. Bottom: Spectrum of the $^{3}\text{He},t$ reaction on PVA.

identical kinematics (lower part of Fig. 1). No transition was observed in $^{138}\text{La}$ for energies between the g.s. and 72 keV. A conservative upper limit from the present experiment for the population of a hypothetic low-energy state can be extracted varying between $B(\text{GT}) = 0.04$ close to the g.s., where the background line is prominent, and $B(\text{GT}) = 0.02$ around $E_{x} = 72$ keV. It is used to estimate an upper limit of the corresponding half life from the relation between $ft$ and $B(\text{GT})$ values (see, e.g., Ref. [11]). For $^{138}\text{La}$ EC decay one obtains upper limits ranging from 3.48 h at $E_{x} = 72$ keV to 1.90 h at $E_{x} = 0$ keV.

On the other hand, excitation of the previously known $1^+$ state in $^{138}\text{La}$ at $E_{x} = 293$ keV was prominently observed (cf. Fig. 1) with $B(\text{GT}) = 0.42$. The exact $B(\text{GT})$ values depend on the model used for conversion of experimental cross sections to transition strengths, but differences between the approaches of [9] and [10] are of the order of 10% in heavy nuclei only, which is of no relevance to the present discussion.

The competing electromagnetic transition of a hypothetic low-energy $1^+$ state to the $^{138}\text{La}$ g.s. would be of $E4/M5$ character. Contributions of $M5$ should be suppressed by several orders of magnitude and are therefore neglected. The structure of the hypothetical $1^+$ state is unknown; for an estimate we assume an $E4$ transition strength of 1 Weisskopf unit. Because of the large atomic number and small excitation energy the decay would be dominated by internal conversion (IC). IC coefficients were calculated with the code BRICC [12]. The resulting half life at $E_{x} = 72$ keV of a hypothetical state would be 8.9 d (and even
larger for lower \(E_x\), still significantly longer than the limit deduced for the EC decay.

Nevertheless, the experimental results \[7\] provide an indirect argument against the existence of another low-lying \(1^+\) state besides the lowest known one at \(E_x = 293\) keV. The structure of the lowest states in \(^{138}\)La can be understood in the simplest approximation as proton-particle, neutron-hole states with respect to the \(N = 82\) closed-shell nucleus \(^{138}\)Ba. The single-particle energies of shells near the Fermi level can be estimated from single-nucleon transfer reactions populating \(^{137}\)Ba and \(^{139}\)La, respectively. The lowest neutron-hole states observed in \(^{137}\)Ba \[13\] are \(2d_{3/2}\) (g.s.), \(3s_{1/2}\) \((E_x = 0.28\) MeV), and \(1h_{11/2}\) \((E_x = 0.66\) MeV). For the proton-particle states in \(^{139}\)La \[14\] one finds \(1g_{7/2}\) (g.s.), \(2d_{5/2}\) \((E_x = 0.17\) MeV), \(3s_{1/2}\) \((E_x = 1.21\) MeV), and \(1h_{11/2}\) \((E_x = 1.44\) MeV). A clear energy gap is observed in both cases suggesting the lowest states in \(^{138}\)La to be formed by the configurations \((\pi g_{7/2} \nu d_{3/2}^{-1})_{2^+,3^+,4^+,5^+}, (\pi g_{7/2} \nu s_{1/2}^{-1})_{3^+,4^+,5^+}, (\pi d_{5/2} \nu d_{3/2}^{-1})_{1^+,2^+,3^+,4^+}, (\pi d_{5/2} \nu s_{1/2}^{-1})_{2^+,3^+}\). Thus, the low-energy spectrum of \(^{138}\)La should consist of the following number of states with a given spin \(J^\pi\) \(= 1^+\) \((1)\), \(J^\pi\) \(= 2^+\) \((3)\), \(J^\pi\) \(= 3^+\) \((4)\), \(J^\pi\) \(= 4^+\) \((3)\), \(J^\pi\) \(= 5^+\) \((1)\). This is exactly what is found for the lowest states in \(^{138}\)La up to an excitation energy of \(E_x = 642\) keV \[6\]. The next-higher states all show negative parity (where known) indicating that their structure involves the \(1h_{11/2}\) orbital.

The experimental observation of only one \(1^+\) state at 293 keV with a rather large GT strength is qualitatively consistent with the above picture of a dominant \((\pi d_{5/2} \nu d_{3/2}^{-1})_{1^+}\) structure. Any further hypothetical \(1^+\) state in \(^{138}\)La at low excitation energies should mix with this one leading to a finite GT strength which can be largely excluded from the sensitivity limits of the (^3He,t) data. As an example, in a two-state model assuming an interaction matrix element \(V = 10\) keV and an energy spacing \(\Delta E = 250\) keV between the two states one would obtain complete mixing with a corresponding share of the GT strength.

As a final remark, evidence against the existence of an intruder \(1^+\) state in \(^{138}\)La as the first excited state is also provided by a study of the \(^{138}\)Ba(p,n\(\gamma\)) reaction \[15\]. In this reaction low-spin states are preferentially excited but no \(\gamma\) transitions consistent with such a picture were found. We conclude that the existence of a low-energy \(1^+\) state in \(^{138}\)La which would affect the cosmochronometer discussed in \[1\] and also the analysis of charged-current reactions as a major nucleosynthesis source of \(^{138}\)La \[3, 4\] is extremely unlikely.
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