Effect of bound state β^- decay and electron capture in the production of ^{208}Pb

Arkabrata Gupta* and S. Sarkar†
Department of Physics, Indian Institute of Engineering Science and Technology, Shibpur, Howrah-711103, India

Chirashree Lahiri‡
Department of Physics, Surendranath Evening College, 24/2 M. G. Road, Kolkata-700009, India.

1. Introduction

It is now a well established fact that in the conventional β^- decay process, the decay of a neutron to proton is accompanied by the creation of an electron and an anti-neutrino in continuum states. However, in the case of stellar plasma, the atoms may remain in fully ionized or partially ionized states, an additional effect comes into the picture. In a high temperature and density stellar environment nuclear β^- decay to the bound states of the ionized atom is another probable, sometimes the most dominant, decay channel. This process can be visualized as a time reversal of electron capture; a nucleus has a possibility to undergo β^- decay by creating an electron in a previously unoccupied atomic orbital instead of the continuum decay. Besides, the phenomenon of electron capture for the ionized atoms is not identical to that of the neutral one. For example, in case of bare atom, electron capture is not possible from the bound electronic shells, as no electrons are present there. However, electron capture from the continuum is a probable channel, as in a stellar plasma the atom is surrounded by the cloud of electrons. Depending on the energetics, sometimes the effect of β^- decay to the bound states and the electron capture becomes dominant enough to change the total half-life of a nucleus. This can cause a considerable change in the nucleosynthesis path. The effect can also be reflected in the abundance flow through a particular nucleosynthesis channel.

In the present work, we studied various nucleosynthesis paths that end up in ^{208}Pb and studied how the effect of the β^- decay to the atomic bound states and the change in electron capture half-lives influence the scenario. As in the high temperature ($\sim 0.1-0.5$ GK) and density ($n_e \sim 10^{26}$gm/cc) environment, most of the atoms become fully ionized, we performed the entire calculation taking all these nuclei in their bare configuration. The decay chain consists of the following channels: β^--decay to both continuum and bound states, α-decay and electron capture. In case of neutral atom, as the electronic shells are filled, the decay to the bound state becomes ruled out, whereas for bare atoms, it has a dominant contribution. For this purpose, we choose a nuclear decay chain consisting of 44 nuclei with a few seed nuclei which are either the remnant of some other isotopic decay chain, or originates from the decay of astrophysical r-process elements.

2. Methodology

In order to calculate the β^- decay to both continuum and bound states, we considered the allowed and first-forbidden β^- transitions only. The decay rates (in sec^{-1}) for allowed (a), non-unique first-forbidden(nu) and unique first-forbidden(u) transitions are given by [1–4]. The expression of transition rate λ is expressed as a product of two parts. The

*Electronic address: arkabratagupta.rs2016@physics.iiests.ac.in
†Electronic address: ss@physics.iiests.ac.in
‡Electronic address: chirashree.lahiri@gmail.com

first part gives the transition rate for the β^- decay to the continuum of the neutral atom. The second part f_m^* is called the lepton phase volume, which incorporates effect of ionization of the atoms. This term can also be expressed as the sum of two terms: one for the decay to continuum and other for the decay to the available vacant atomic states of the ionized atom. The methodology is described in Ref.[4] in detail. The α-decay half-lives are taken from the Ref.[5]. Calculation procedure of electron capture half-lives are adopted from Ref.[1].

3. Results and Discussion

We assumed that, initially at $t = 0$, only a few seed elements are present in the environment. Depending on the temperature-density condition, we considered that all these seed nuclei are in their bare configuration. In the figure, the growth and decay of bare ^{228}Ra (dotted line) is compared to the neutral ^{228}Ra (continuous line) with time. In this case, the temperature of the environment is assumed 5×10^8 K and density 10^{26} gm/cc. Note that, for the nucleosynthesis and decay calculation of neutral ^{228}Ra, the seed nuclei are also chosen in their neutral configuration. In the y-axis, relative abundance of the element with respect to the total initial abundances are shown. It is visible that after t=10^5 seconds, two scenarios differ substantially from each other. The reason behind this trend is that, the half life of neutral ^{228}Ra is 5.75 years, which drops considerably for bare atoms to 2 days due to the massive contribution of the β^--decay to the atomic bound states[4]. Due to the faster decay of bare ^{228}Ra, mass accumulation of the element is lower compared to the same for neutral atom. Note that, the abundance does not fall with time. The reason behind this is another short lived seed ^{232}Ac that decays to ^{232}Th. ^{232}Th is an extremely long lived element with a half-life of 14Gy. This isotope can decay through emitting α particles that supply constant abundance feeding to ^{228}Ra.

From the trend of the figure of this simple model calculation, it can be inferred that the presence of bound state decay has an impact over the nucleosynthesis path. Similarly, we have investigated the effect of electron capture in the nucleosynthesis chain, wherever applicable. Our objective is to show how this phenomena effects the production and the final abundance of ^{208}Pb. Depending on the temperature and density of the environment, an element can exist in different ionized states that can be obtained using Saha ionization formula. Therefore the effect of β^- decay to the bound states in different temperature-density scenario is studied and its impact on the observed abundance of ^{208}Pb is examined. However, more realistic calculations of relative abundance is necessary. Work is in progress in this direction.

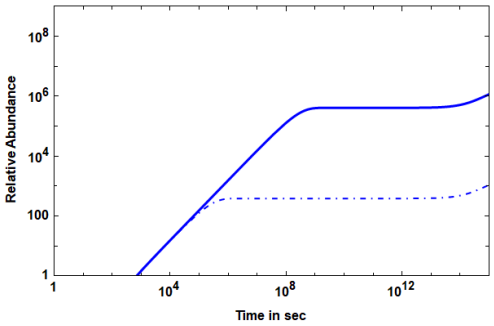

FIG. 1: Relative abundances as a function of time for ^{228}Ra.

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