# Nucleosynthesis of <sup>92</sup>Nb and the relevance of the low-lying isomer at 135.5 keV

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**Background:** Because of its half-life of about 35 million years,  ${}^{92}$ Nb is considered as a chronometer for nucleosynthesis events prior to the birth of our sun. The abundance of  ${}^{92}$ Nb in the early solar system can be derived from meteoritic data. It has to be compared to theoretical estimates for the production of  ${}^{92}$ Nb to determine the time between the last nucleosynthesis event before the formation of the early solar system.

**Purpose:** The influence of a low-lying short-lived isomer on the nucleosynthesis of  ${}^{92}$ Nb is analyzed. The thermal coupling between the ground state and the isomer via so-called intermediate states affects the production and survival of  ${}^{92}$ Nb.

**Method:** The properties of the lowest intermediate state in  ${}^{92}$ Nb are known from experiment. From the lifetime of the intermediate state and from its decay branchings, the transition rate from the ground state to the isomer and the effective half-life of  ${}^{92}$ Nb are calculated as a function of the temperature.

**Results:** The coupling between the ground state and the isomer is strong. This leads to thermalization of ground state and isomer in the nucleosynthesis of  ${}^{92}$ Nb in any explosive production scenario and almost 100 % survival of  ${}^{92}$ Nb in its ground state. However, the strong coupling leads to a temperature-dependent effective half-life of  ${}^{92}$ Nb which makes the  ${}^{92}$ Nb survival very sensitive to temperatures as low as about 8 keV, thus turning  ${}^{92}$ Nb at least partly into a thermometer.

**Conclusions:** The low-lying isomer in  ${}^{92}$ Nb does not affect the production of  ${}^{92}$ Nb in explosive scenarios. In retrospect this validates all previous studies where the isomer was not taken into account. However, the dramatic reduction of the effective half-life at temperatures below 10 keV may affect the survival of  ${}^{92}$ Nb after its synthesis in supernovae which are the most likely astrophysical site for the nucleosynthesis of  ${}^{92}$ Nb.

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## I. INTRODUCTION

<sup>92</sup>Nb is a slightly neutron-deficient odd-odd (Z = 41, N = 51) nucleus with a long half-life of  $t_{1/2} = 3.47 \times$  $10^7$  y. It decays preferentially by electron capture to  $^{92}$ Zr whereas the energetically also possible  $\beta^-$ -decay to  ${}^{92}$ Mo was not observed. The long half-life of <sup>92</sup>Nb results from the high  $J^{\pi} = 7^+$  of the <sup>92</sup>Nb ground state which suppresses  $\beta$ -decays to low-lying states in  $^{92}$ Zr or  $^{92}$ Mo. Contrary to the <sup>92</sup>Nb ground state, the first excited state of <sup>92</sup>Nb at  $E^* = 135.5 \text{ keV}$  has a low  $J^{\pi} = 2^+$ . Thus, direct electromagnetic M5 or E6 transitions to the  $J^{\pi} = 7^+$ ground state are highly suppressed, and the  $2^+$  isomer decays also by electron capture to  ${}^{92}$ Zr with a short half-life of  $t_{1/2} = 10.15$  d which is 9 orders of magnitude smaller than the half-life of the <sup>92</sup>Nb ground state. Except explicitly noted, all properties of  ${}^{92}$ Nb have been taken from the ENSDF database [1] which is based on the Nuclear Data Sheets [2–5].

Unstable nuclei with half-lives of the order of several ten million years are considered as potential chronometers for the time between the last nucleosynthesis event and the birth of our sun. For this purpose the production of these unstable nuclei is compared to the abundance in the early solar system which can be derived from meteoritic data (e.g., [6-12]). Unfortunately, in the case of  ${}^{92}\text{Nb}$ , the production remains relatively uncertain. It is clear that  ${}^{92}\text{Nb}$  cannot be produced in the two main neutron capture processes. The nucleosynthesis path in the slow neutron capture process (*s*-process) bypasses  ${}^{92}\text{Nb}$ , and  ${}^{92}\text{Nb}$  is shielded from production in the rapid neutron capture process (*r*-process) by the stable isobar  ${}^{92}\text{Zr}$ . The stable isobar  ${}^{92}\text{Mo}$  shields  ${}^{92}\text{Nb}$ also from production under conditions of the rapid proton capture process (*rp*-process). Thus, only very few astrophysical processes remain as candidates for the nucleosynthesis of  ${}^{92}\text{Nb}$  which are in particular the so-called *p*-process and neutrino-induced nucleosynthesis.

Under *p*-process conditions <sup>92</sup>Nb may be produced by the <sup>93</sup>Nb( $\gamma$ ,n)<sup>92</sup>Nb reaction although further destruction by the <sup>92</sup>Nb( $\gamma$ ,n)<sup>91</sup>Nb reaction could occur. Alternatively, the <sup>91</sup>Zr(p, $\gamma$ )<sup>92</sup>Nb reaction may produce <sup>92</sup>Nb in a proton-rich *p*-process environment. As astrophysical sites for the *p*-process, supernova (SN) explosions of corecollapse type (SN type-II) or thermonuclear explosions of white dwarfs (SN type Ia) have been suggested (e.g., [13– 16]). Very recently it has been emphasized that <sup>92</sup>Nb can be used to constrain models of *p*-process nucleosynthesis [17].

Neutrino-induced nucleosynthesis of <sup>92</sup>Nb occurs via the <sup>92</sup>Zr( $\nu_e, e^-$ )<sup>92</sup>Nb or <sup>93</sup>Nb( $\nu, \nu' n$ )<sup>92</sup>Nb reactions where the high neutrino flux is provided by a forming neutron star after a core-collapse SN [18–22]. In any case, the nucleosynthesis of <sup>92</sup>Nb occurs in an explosive scenario with timescales of the order of 1 second and temperatures of at least 1 billion Kelvin ( $T_9 > 1, kT \approx 86 \text{ keV}$ ).

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The nucleosynthesis of  $^{92}$ Nb may be significantly influenced by the properties of the low-lying  $J^{\pi} = 2^+$  isomer at  $E^* = 135.5 \,\mathrm{keV}$  which is coupled to the  $J^{\pi} = 7^+$ ground state via so-called intermediate states (IMS). Interestingly, most of the previous studies did not take into account this isomer; up to now only Meyer [22] has pointed out that "Accurate predictions of the <sup>93</sup>Nb/<sup>92</sup>Nb production ratio, then, will require an appropriate treatment of the isomeric state in the nucleosynthesis calculations". In general, three questions have to be answered: (i) What is the production ratio between  $7^+$  ground state and  $2^+$  isomer? (ii) How is the production ratio during the explosive production affected by thermal couplings via the IMS? (iii) Does the coupling via the IMS affect the later survival of <sup>92</sup>Nb? In advance, I provide the answers to these questions from the following discussion of the properties of the IMS with  $J^{\pi} = 4^+$  at  $E^* = 480.3 \text{ keV}$ : (i) and (ii): The coupling between 7<sup>+</sup> ground state and  $2^+$  isomer is so strong that thermal equilibrium between ground state and isomer is reached almost instantaneously and maintained at least down to temperatures of the order of 20 keV. These low temperatures correspond to an almost negligible Boltzmann ratio of  $n(2^+)/n(7^+) = (5/15) \times \exp(-E^*/kT) \lesssim 10^{-4}$ . Thus, almost 100% of the produced <sup>92</sup>Nb survives, independent of the production ratio of isomer and ground state. (iii) The strong coupling between  $2^+$  isomer and  $7^+$  ground state leads to a strongly temperature-dependent effective half-life of <sup>92</sup>Nb. Already at kT = 8.3 keV, the effective half-life is reduced by one order of magnitude, and at  $kT = 10.4 \,\mathrm{keV}$  the reduction of the effective half-life reaches a factor of 1000. This may turn <sup>92</sup>Nb from a chronometer into a sensitive thermometer for the thermal history between the nucleosynthesis of  $^{92}$ Nb in an explosive astrophysical event and the formation of the early solar system.

### II. COUPLING BETWEEN THE GROUND STATE AND THE ISOMER VIA INTERMEDIATE STATES

Because of the spin difference  $\Delta J = 5$  between the 7<sup>+</sup> ground state and  $2^+$  isomer, a direct  $\gamma$ -ray (M5 or E6) transition is strongly suppressed by the electromagnetic selection rules. Any transition between ground state and isomer must proceed via IMSs at higher excitation energies which are excited by thermal photons. The number of photons in a thermal stellar photon bath decreases exponentially with energy E; thus, typically the IMS with the lowest excitation energy dominates the transition rates at stellar temperatures. A careful inspection of the level scheme of <sup>92</sup>Nb shows that the lowest IMS is the 4<sup>+</sup> state at  $E^* = 480.3 \,\text{keV}$ . All levels below the IMS with J < 4 decay finally to the 2<sup>+</sup> isomer ("low-J states" in Fig. 1, left part) whereas the only level with J > 4 below the IMS decays only to the 7<sup>+</sup> ground state ("high-J states").

It is interesting to note that there are only two further states in <sup>92</sup>Nb above the IMS and below an excitation energy of 1 MeV. The 6<sup>+</sup> state at 501.3 keV is a high-J state which decays exclusively to the 7<sup>+</sup> ground state, and the (1<sup>+</sup>, 2<sup>-</sup>) state at 975.0 keV is a low-J state which decays exclusively to the 2<sup>-</sup> state at 225.8 keV. Thus, the 4<sup>+</sup> state at 480.3 keV is the only IMS in <sup>92</sup>Nb below  $E^* = 1$  MeV, and the coupling between ground state and isomer under stellar conditions is essentially defined by this IMS.

The lifetime and the decay branches of the 4<sup>+</sup> IMS are known from experiment [1]. The decay branches have been measured in several independent  $(p,n\gamma)$ ,  $(d,t\gamma)$ , and  $(\alpha,n\gamma)$  experiments, and good agreement was found [1]:  $b_{\gamma} = 23.7 \pm 3.2\%$  for the transition to the 5<sup>+</sup> state at  $E^* = 357.4 \text{ keV}$  and  $b_{\gamma} = 76.3 \pm 3.2\%$  for the transition to the 3<sup>+</sup> state at  $E^* = 285.7 \text{ keV}$ . The 5<sup>+</sup> state decays with 100% to the 7<sup>+</sup> ground state whereas the 3<sup>+</sup> state decays with 100% to the 2<sup>+</sup> isomer (see Fig. 1).

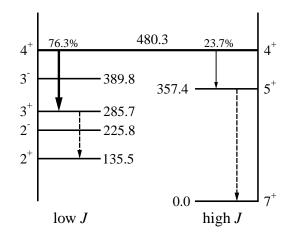


FIG. 1. Partial level scheme of  $^{92}$ Nb (approximately to scale; from [1]). The IMS with  $J^{\pi} = 4^+$  at  $E^* = 480.3$  keV is marked by a bold horizontal line. Primary decays from the IMS are shown with full arrows; secondary  $\gamma$ -rays are shown with dashed arrows. Except for the ground state, the spin asignments are only tentative but "very probably" according to a comment in [1]. Therefore, the parentheses in the tentative  $(J)^{\pi}$  assignments are omitted in this work. The influence of  $J^{\pi}$  assignments on the results of this work is restricted to statistical weights and thus remains limited when compared to the dominating Boltzmann factors.

The lifetime of the IMS is reported only in an unpublished laboratory report USIP-74-17 of the University of Stockholm which is fortunately available on the web [23]. A half-life of  $t_{1/2} = 0.62 \pm 10$  (without units) is given in Table VI of [23]. However, from the text in [23] it becomes obvious that the half-life is 0.62 ps, corresponding to M1 transition strengths of the order of several  $\mu_N^2$  for the above mentioned transitions. Surprisingly, a half-life of 0.62 ns has been adopted in [5], and this value persists until now [1–4].

At stellar temperatures, thermal equilibrium within

states with low J on the one hand and within high Jstates on the other hand is established almost instantaneously because the levels are connected by allowed  $\gamma$ transitions. As a consequence, the transition rate from the 7<sup>+</sup> ground state to the 2<sup>+</sup> isomer depends on the stellar integrated cross section  $I^{*}_{\sigma}$  of the IMS

$$I_{\sigma}^{*} = g \left(\frac{\pi\hbar c}{E^{*}}\right)^{2} \frac{\Gamma_{\gamma}^{\Sigma J_{\rm IMS} \to J_{j} \to J_{2}+} \Gamma_{\gamma}^{\Sigma J_{\rm IMS} \to J_{k} \to J_{7}+}}{\Gamma} \quad (1)$$

with the partial radiation width  $\Gamma_{\gamma}^{\Sigma J_{\text{IMS}} \to J_j \to J_{2^+}}$  summed over all partial widths  $\Gamma_{\gamma}^{J_{\text{IMS}} \to J_j}$  leading finally to the 2<sup>+</sup> isomer and a similar definition for  $\Gamma_{\gamma}^{\Sigma J_{\text{IMS}} \to J_k \to J_{7^+}}$  for transitions to the  $7^+$  ground state. Note that the properties of the thermally excited states with  $J_i$  and  $J_k$  do not appear in Eq. (1). The reason for this cancellation is discussed in detail in [24]. The spin factor in Eq. (1)is given by  $g = (2J_{\text{IMS}} + 1)/(2J_{\text{g.s.}} + 1) = 9/15 = 0.6$ [24, 25]. For the transition from the 7<sup>+</sup> ground state to the  $2^+$  isomer the integrated cross section via the  $4^+$ IMS is  $I_{\sigma}^* = 133 \,\mathrm{eV} \,\mathrm{fm}^2$  with an uncertainty of about 20 % which is given by the 16% uncertainty of the lifetime of the IMS and the 13% uncertainty of the branching ratio. Values of the same order of magnitude have been obtained for integrated cross sections in the neighboring odd-odd nucleus  $^{108}$ Ag [26], whereas this result is about a factor of 20 - 100 larger than the lowest experimentally known IMSs in the heavy odd-odd nuclei <sup>176</sup>Lu [27] and <sup>180</sup>Ta [28, 29] which are located at slightly higher excitation energies. The lowest IMS candidate in <sup>180</sup>Ta is located at a similar excitation energy as the  $4^+$  IMS in <sup>92</sup>Nb; its integrated cross section is almost six orders of magnitude smaller [24]. Also relatively small values have been estimated for a low-lying K-mixing IMS in  $^{176}Lu$ [30]. Very recently, IMSs have also been searched for in  $^{186}$ Re [31].

#### III. STELLAR REACTION RATE AND EFFECTIVE HALF-LIFE

The reaction rate  $\lambda^*(T)$  for the  $7^+ \rightarrow 2^+$  transition via the 4<sup>+</sup> IMS at  $E^* = 480.3 \,\text{keV}$  is given by

$$\lambda^*(T) = c \int n_{\gamma}(E_{\gamma}, T) \,\sigma^*(E_{\gamma}) \,dE_{\gamma}$$
$$\approx c \,n_{\gamma}(E^*, T) \,I_{\sigma}^* \tag{2}$$

with the integrated cross section  $I_{\sigma}^*$  from Eq. (1) and thermal photon density

$$n_{\gamma} (E_{\gamma}, T) dE_{\gamma} = \frac{1}{\pi^2} \frac{1}{(\hbar c)^3} \frac{E_{\gamma}^2}{\exp(E_{\gamma}/kT) - 1} dE_{\gamma}.$$
 (3)

The result is shown in Fig. 2. One finds a dramatic variation of the transition rate as a function of temperature (given as thermal energy kT throughout this paper). Already at kT = 50 keV the rate exceeds  $10^6/\text{s}$ , thus leading to thermalization of isomer and ground state under any typical conditions of explosive nucleosynthesis. Consequently, the production ratio between  $2^+$  isomer and  $7^+$  ground state of  ${}^{92}$ Nb does not play any role for the nucleosynthesis of  ${}^{92}$ Nb because the properties of the  $4^+$ IMS ensure thermal equilibrium within less than 1 microsecond for any temperature above kT = 50 keV. In retrospect, this validates all previous studies which did not take into account the isomer in the production of  ${}^{92}$ Nb.

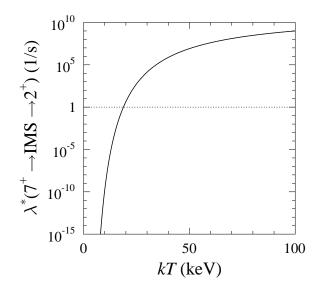


FIG. 2. Stellar transition rate  $\lambda^*$  for the transition from the 7<sup>+</sup> ground state to the 2<sup>+</sup> isomer via the 4<sup>+</sup> IMS in <sup>92</sup>Nb. The horizontal line at  $\lambda^* = 1.0/s$  marks the typical timescale of supernova explosions.

For completeness it should be mentioned that the rate for the reverse transition from the  $2^+$  isomer to the  $7^+$ ground state can be derived in the same way according to Eqs. (1) and (3). As a result, the reverse rate is related to the forward rate by detailed balance [25].

After the explosive nucleosynthesis event the temperature drops. As soon as the rate  $\lambda^*$  falls below the timescale of the explosive nucleosynthesis event, thermal equilibrium between the  $2^+$  isomer and  $7^+$  ground state cannot persist. This happens at the relatively low temperature of  $kT \approx 19 \,\mathrm{keV}$  for a typical supernova explosion with timescales of the order of one second. At this low temperature the ratio between isomer and ground state is given by the Boltzmann factor  $n(2^+)/n(7^+) = (5/15) \times \exp(-E^*/kT) \lesssim 10^{-4}$ . Thus, practically all <sup>92</sup>Nb survives in the 7<sup>+</sup> ground state. Because of the steep temperature dependence of the reaction rate  $\lambda^*$ , the freeze-out temperature does not vary dramatically for a broader range of explosion timescales. An increase (decrease) of the explosive timescale by a factor of 10 reduces (increases) the freeze-out temperature by less than 2 keV which does not affect the almost 100% survival probability of <sup>92</sup>Nb in its 7<sup>+</sup> ground state.

Although thermal equilibrium between the  $7^+$  ground state and the  $2^+$  isomer cannot be maintained at low temperatures, there is still a tiny probability for a transition between ground state and isomer. This leads to a temperature-dependent effective half-life of <sup>92</sup>Nb and may affect the survival of <sup>92</sup>Nb in the cooling phase after its explosive production or in any later re-heating. Qualitatively, as long as the transition rate  $\lambda^*$  is much smaller than the  $\beta$ -decay constant  $\lambda_{\beta}(7^+) = 6.3 \times 10^{-16}$ /s, the effective half-life remains constant at its laboratory value. At about 8 keV  $\lambda^*$  becomes comparable to  $\lambda_{\beta}(7^+)$ , and thus the  $2^+$  isomer is weakly populated. Now the  $\beta$ decay rate  $\lambda_{\beta}(2^+) = 7.9 \times 10^{-7}$ /s is faster than the transition back to the ground state which leads to  $\beta$ -decay of the isomer and a reduction of the effective half-life of <sup>92</sup>Nb which scales with the transition rate  $\lambda^*$ . At higher temperatures above 20 keV, thermal equilibrium is established, and here the effective half-life scales with the Boltzmann factor of the isomer and its  $\beta$ -decay constant  $\lambda_{\beta}(2^+)$ . The resulting effective half-life of <sup>92</sup>Nb is shown in Fig. 3.

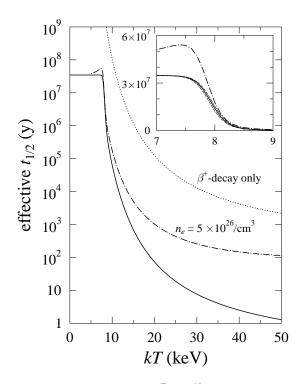


FIG. 3. Effective half-life  $t_{1/2}^{\rm eff}$  of <sup>92</sup>Nb as a function of temperature. The inset shows the dramatic decrease of the effective half-life around  $kT \approx 8 \,\mathrm{keV}$  and the nuclear uncertainties of a 20% increased or decreased coupling (dashed lines). An upper limit from  $\beta^+$ -decay (without electron capture) is shown as dotted line. The dash-dotted line represents an intermediate plasma density of  $n_e = 5 \times 10^{26} / \mathrm{cm}^3$ . Further discussion see text.

Unfortunately, there is a further complication. The  $\beta$ -decay constants  $\lambda_{\beta}(7^+)$  and  $\lambda_{\beta}(2^+)$  in <sup>92</sup>Nb are dominated by electron capture (mainly from the *K*-shell). The binding energy of a *K*-electron in <sup>92</sup>Nb is 19.0 keV. Thus, at higher temperatures the  $\beta$ -decay constants of ground state and isomer will decrease significantly. This effect

depends on the ionization state of  $^{92}$ Nb which in turn depends on temperature and electron density of the surrounding plasma. Independent of temperature and density, the 2<sup>+</sup> isomer has a small  $\beta^+$ -decay branching with a branching ratio of  $5.9 \times 10^{-4}$ , whereas  $\beta^+$ -decay has not been observed for the 7<sup>+</sup> ground state. An extreme upper limit of the effective half-life of  $^{92}$ Nb can thus be calculated from the  $\beta^+$ -decay branch of the isomer. This is shown as dotted line in Fig. 3.

It is difficult to provide a general estimate of the effective half-life of <sup>92</sup>Nb under realistic astrophysical conditions as long as the astrophysical scenario and the resulting plasma density are not known. Nevertheless, it can be concluded that the steep drop of the effective half-life around  $kT \approx 8 \,\mathrm{keV}$  is real because at these temperatures the K-shell of  $^{92}$ Nb is not yet fully ionized. As an example, the effective half-life is also shown for an intermediate electron density  $n_e = 5 \times 10^{26} / \text{cm}^3$  in Fig. 3. One can see a small increase of the effective half-life around  $kT \approx 7 \,\mathrm{keV}$  because of the starting ionization of the Kshell. This increase is followed by a steep decrease around  $kT \approx 8 \text{ keV}$  which is governed by the transition rate from the  $7^+$  ground state to the  $2^+$  isomer; even when partly ionized, the  $\beta$ -decay of the isomer will still be sufficiently fast (see the above qualitative discussion of the effective half-life).

Finally, the inset of Fig. 3 shows clearly that the dominating uncertainties for the effective half-life of  $^{92}$ Nb result from the astrophysical conditions whereas the nuclear uncertainties are marginal. Nevertheless, an independent confirmation of the unpublished lifetime of the  $4^+$  IMS in  $^{92}$ Nb from [23] is desirable.

#### IV. CONCLUSIONS

The present study has shown that the low-lying  $2^+$  isomer at  $E^* = 135.5 \text{ keV}$  does not play a significant role in the production of <sup>92</sup>Nb in any explosive scenario. Thermal equilibrium is maintained down to low temperatures below  $kT\approx 19\,{\rm keV}$  where the Boltzmann population of the  $2^+$  isomer is already practically negligible. Thus the present study validates in retrospect the previous nucleosynthesis studies of <sup>92</sup>Nb where the isomer was not taken into account. However, the coupling to the isomer leads to a dramatically reduced effective half-life of  $^{92}$ Nb at temperatures as low as  $kT \approx 8$  keV. Thus, any re-heating of the freshly synthesized  $^{92}$ Nb above 8 keV, e.g. in the X-ray emitting supernova ejecta with its typical temperatures in the low keV range [32, 33], will reduce its abundance significantly. This turns <sup>92</sup>Nb at least partly from a chronometer to a thermometer for the thermal evolution after the last nucleosynthesis event before the formation of our solar system.

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