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The decay energy of the pure s-process nuclide ^{123}Te

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ABSTRACT

A direct and high-precision measurement of the mass difference of ^{123}Te and ^{123}Sb has been performed with the Penning-trap mass spectrometer SHIPTRAP using the recently introduced phase-imaging ion-cyclotron-resonance technique. The obtained mass difference is 51.912(67) keV/c^2. Using the masses of the neutral ground states and the energy difference between the ionic states an effective half-life of ^{123}Te has been estimated for various astrophysical conditions. A dramatic influence of the electron capture process on the decay properties of ^{123}Te in hot stellar conditions has been discussed.

1. Introduction

Until recently the ground state decay properties of the nuclide ^{123}Te have been rather ambiguous. The lowest precise experimental value for the half-life $T_{1/2} = 1.24(10) \cdot 10^{13}$ y [1] and the recently obtained limits of $> 3.2 \cdot 10^{16}$ y [2] and $> 9.2 \cdot 10^{16}$ y [3] are much longer than the age of the Universe of $1.38 \cdot 10^{10}$ y determined from the WMAP-evaluation [4]. Although the decay schemes for ^{123}Te and ^{123}Sb are known, the mass difference of ^{123}Te and ^{123}Sb, which governs the half-life of ^{123}Te, has not yet been measured directly. Its value of 52.7(1.6) keV was evaluated on the basis of available (n,γ)-reaction data [5].

Since the expected mass difference, i.e. Q-value, between mother and daughter nucleus is close to the energetic region of the total electron binding energies for Te, accurate and precise data are demanded. Previous direct measurements by Penning traps showed the differences of 30–40 keV for measured data for different nuclides [6–8] in comparison with the AME [9]. Since this difference is on the level of the expected absolute value of Q for ^{123}Te, a direct Penning-trap measurement of this value is required.

All the attempts of determining the half-life concern the ground state of neutral ^{123}Te. However, in stars nuclides are ionized leading to a certain charge-state distribution, which depends on the temperature of the stellar interior. The decay energy for the electron capture from ionic ground states is expected to be smaller than that for neutral states. This substantially increases the half-life of ionized ^{123}Te. Meanwhile, it was noted that in hot stellar conditions nuclei with populated excited states can undergo electron capture, whose strength depends on the excitation energy, the mass difference between the neutral mother and daughter atoms, the ionic charge state, and the astrophysical conditions [10–14]. Such a possibility was demonstrated in [15] for long-lived beta-emitters. The mass difference between ionic states depends on the mass difference of the neutral atoms and the excitation energy of the nuclear state, which can be populated in the stellar environment. Accurate knowledge of the former is of importance for the capture process, especially for small decay energies close to the binding energy of K-electrons equal to 30.49 keV for the electron capture in ^{123}Te.

The nuclide ^{123}Te and its neighboring tellurium isotopes with mass numbers of $A = 122$ and 124 are pure s-process nuclides produced only in the slow neutron capture (s-process) in stars. Therefore, an investigation of the decay-branches, attributed to the electron capture from excited states, impossible under terrestrial

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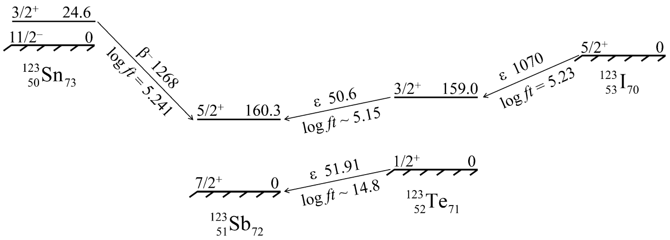

Fig. 1. Decay scheme for isobaric nuclides with mass number $A = 123$. Spectroscopic data are taken from [16]. The Q-value of 51.91 keV of the transition between the neutral ground states was obtained in this work. The $\log ft$ for the transition from the 159 keV excited state was obtained as an averaging from the known $3/2^+ \to 5/2^+$-transitions in the isobaric mass chain with the additional correction to the spin factor (see text). All energy values for the states and decay transitions are given in keV.

conditions, can shed light on the production and depletion of tellurium isotopes in stars.

In this letter we report the first direct and accurate measurement of the mass difference of ^{123}Te and ^{123}Sb. With our reliable result the energy difference between highly ionized atoms was calculated and the effective half-life of ^{123}Te evaluated. The role of the electron-capture process from excited states of ^{123}Te in stellar conditions is discussed.

2. Expected properties of ^{123}Te under hot stellar conditions

Known information about low energy decay schemes of isobaric nuclides with mass number $A = 123$ under terrestrial (i.e. neutral) conditions is shown in Fig. 1.

The first excited states in ^{123}Te and ^{123}Sb have energies of 159.02(2) and 160.33(5) keV. They are strongly populated in the allowed beta-transformations from ^{123}I and ^{123}Sn. These excited states with very short half-lives of 196 and 610 ps, respectively, can be thermally populated in hot stellar conditions according to Eq. (1) [10]:

$$\eta_i = \frac{(2I_i^* + 1)\exp[-E_i^*/kT]}{\sum_j (2I_j^* + 1)\exp[-E_j^*/kT]}, \tag{1}$$

where η_i is the population of the ith-level with energy E_i^* and spin I_i^* at temperature T, and k stands for the Boltzmann constant. The sum over i also includes the ground state. Fig. 1 shows that the 159 keV excited state of ^{123}Te, being quickly populated in the hot stellar interior, can decay via electron capture to both the ground and the 160.3 keV excited state in ^{123}Sb. It predominantly decays to the latter because of the allowed character of the transition $3/2^+ \to 5/2^+$. The transition to the ground state as well as the β^--transition from the 160.3 keV excited state of ^{123}Sb to the ground state of ^{123}Te are of 2nd-order forbidden type and thus are much weaker. The transition probability or the comparative half-life ft for the allowed transition from the 159 keV state can be predicted reliably based on similar $5/2^+ \leftrightarrow 3/2^+$ transitions in $A = 123$ mass region. Under terrestrial conditions this transition is not observed because of a strongly predominant γ-transition probability from the short-lived 159 keV state with $T_{1/2} = 196$ ps to the ground state in ^{123}Te.

The expected $\log ft$ for the $^{123}\text{Te}^*(3/2^+, 159\ \text{keV}) \to {}^{123}\text{Sb}^*(5/2^+, 160.3\ \text{keV})$ transition between the neutral states is about 5.15. It can be deduced from an averaging $\log ft$-values in $A = 123$ mass region (see Fig. 1) taking into account that the $\log ft$-value for the inverse transition $3/2^+ \to 5/2^+$ for ^{123}Te and ^{123}I should be 5.05 according to the equation $\log ft_{(f \to i)} = \log ft_{(i \to f)} + \log\{(2J_f + 1)/(2J_i + 1)\}$.

As can be seen in Fig. 1 the ft-value for the allowed $3/2^+(^{123}\text{Te}) \to 5/2^+(^{123}\text{Sb})$ transition is by nine orders of magnitude smaller than for the transition $1/2^+ \to 7/2^+$ between the ground states [16]. Therefore even a very small thermal population of the 159 keV state can substantially increase the effective electron capture probability for ^{123}Te.

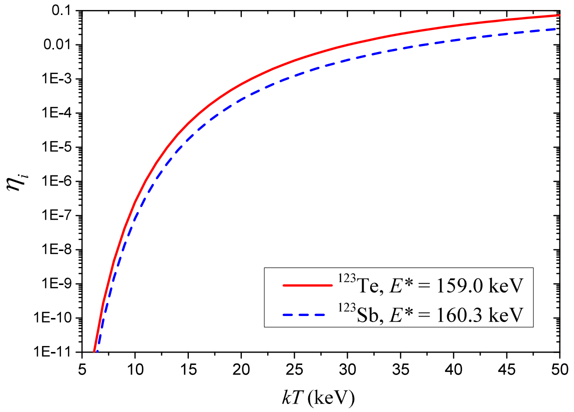

Fig. 2. Temperature dependence of the population coefficient η_i for the 159.0 keV level in ^{123}Te and the 160.3 keV level in ^{123}Sb, respectively. Temperature is expressed in eV units using Boltzmann constant k.

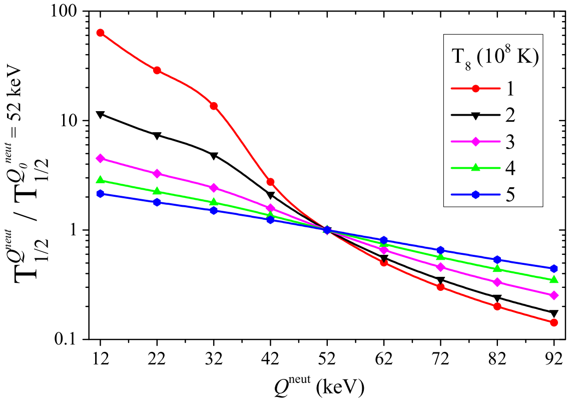

Fig. 3. Effective half-life of ^{123}Te in dependence on Q^{neut}-value. All the data points are normalized to the effective half-life of ^{123}Te with $Q_0^{neut} = 52$ keV. The half-lives are calculated with matter density $\rho = 10^3$ g/cm^3 and for various stellar temperatures in units of 10^8 K.

In Fig. 2 the population coefficient values η_i of the excited states in ^{123}Te and ^{123}Sb calculated by using Eq. (1) at different temperatures are shown. One may notice that the states population varies significantly with the temperature. At the same time, due to the rather large matrix element of the γ-transition of the excited states, this population is attained very rapidly even at moderate temperatures.

On account of such information, the decay properties of ^{123}Te in stellar conditions are dramatically different in comparison with the terrestrial ones, and therefore the electron capture from the excited states of ^{123}Te becomes a crucial decay channel.

In Fig. 3 one can clearly see the dependence of the effective half-life of ^{123}Te on the Q-values for various stellar temperature conditions. For example, there would be almost two orders of mag-