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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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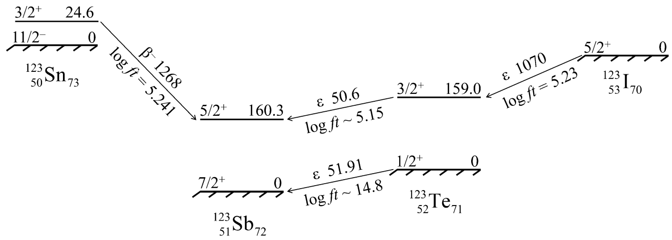

Fig. 1. Decay scheme for isobaric nuclides with mass number $A = 123$. Spectroscopic data are taken from [16]. The Q-value of 51.91 keV of the transition between the neutral ground states was obtained in this work. The $\log ft$ for the transition from the 159 keV excited state was obtained as an averaging 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}Te$^*(3/2^+, 159$ keV$) \to$ ^{123}Sb$^*(5/2^+, 160.3$ 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 $3/2^+(^{123}\mathrm{Te}) \to 5/2^+(^{123}\mathrm{Sb})$ 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.

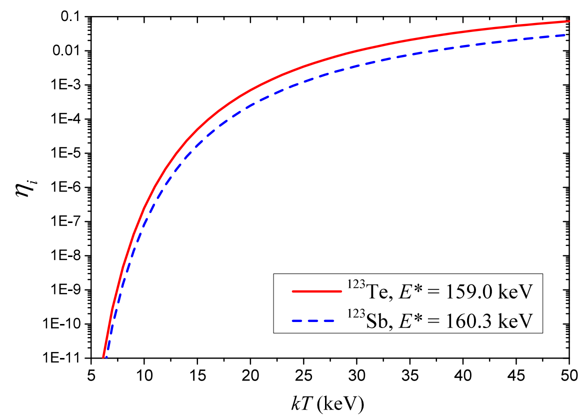

Fig. 2. Temperature dependence of the population coefficient η_i for the 159.0 keV level in ^{123}Te and the 160.3 keV level in ^{123}Sb, respectively. Temperature is expressed in eV units using Boltzmann constant k.

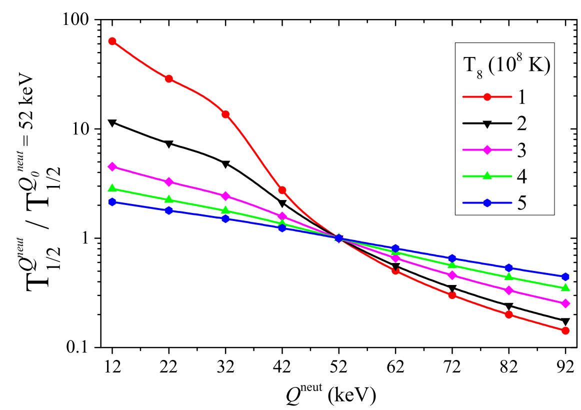

Fig. 3. Effective half-life of ^{123}Te in dependence on Q^{neut}-value. All the data points are normalized to the effective half-life of ^{123}Te with $Q_0^{neut} = 52$ keV. The half-lives are calculated with matter density $\rho = 10^3$ g/cm^3 and for various stellar temperatures in units of 10^8 K.

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-

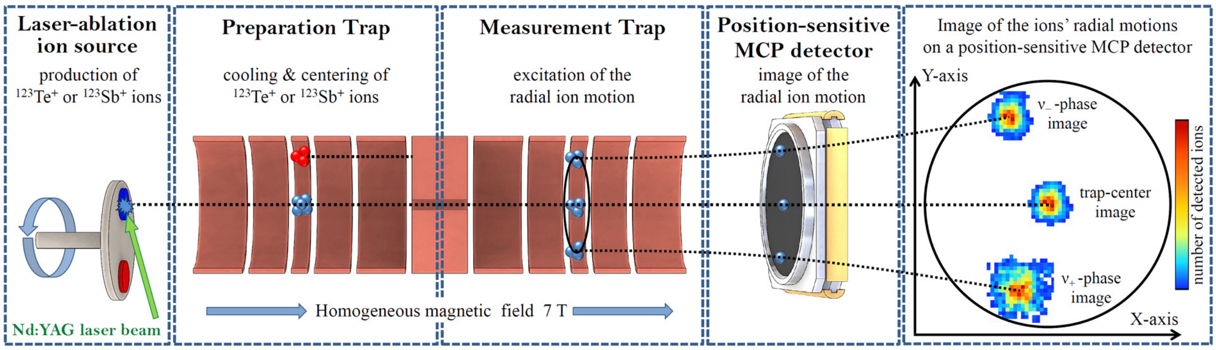

Fig. 4. Schematic of the SHIPTRAP setup used for the determination of the Q-value of the electron capture in ^{123}Te (see text for details). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

nitude change in the half-life if the Q^{neut}-value was 12 keV. That fact emphasizes the necessity of the accurate Q^{neut}-value measurement of ^{123}Te.

3. Mass-difference measurement

A determination of the atomic mass difference between ^{123}Te and ^{123}Sb was performed with the Penning-trap mass spectrometer SHIPTRAP [17] by measuring the cyclotron-frequency ratio of ^{123}Te and ^{123}Sb ions, $R = \nu_c(^{123}\text{Sb}^+)/\nu_c(^{123}\text{Te}^+)$, using the recently developed phase-imaging ion-cyclotron-resonance technique (PI-ICR) [18,19]. The cyclotron frequency ν_c of an ion with mass m and charge q in a magnetic field with strength B, given by $\nu_c = qB/(2\pi m)$, was determined as the sum of the two trap radial-motion frequencies: magnetron frequency ν_- and modified cyclotron frequency ν_+, i.e., $\nu_c = \nu_- + \nu_+$ [20]. A schematic of the experimental setup is presented in Fig. 4. Singly-charged ions of ^{123}Te and ^{123}Sb were alternately produced with a laser-ablation ion source [21] by irradiating the corresponding Te and Sb samples with a frequency-doubled Nd:YAG laser beam at $\lambda = 532$ nm. For the production of the Sb-sample, a piece of natural Sb in metallic crystal form was used. Since the natural abundance of ^{123}Te is only 0.9% a few milligrams of enriched metallic powder with over 70% enrichment of ^{123}Te was compressed into a pellet with a diameter of 2 mm to assure sufficiently high ion production. After singly-charged ions had been produced they were transferred from the ion source into the preparation trap (PT) for cooling and centering via mass-selective buffer-gas cooling (blue colored bunch of ions in the center of PT in Fig. 4) [22]. As shown in Fig. 4 after purification only the ions of interest pass through the diaphragm and are captured in the measurement trap (MT). The mass resolving power of the mass-selective buffer-gas cooling technique reaches 10^5, thus the ions which are not centered (off-axis red colored bunch of ions in Fig. 4) after ejection hit the wall of the diaphragm and thus get removed.

After the ions were captured in the MT the coherent components of their magnetron and axial motions were damped via dipolar rf-pulses at the corresponding frequencies to amplitudes of about 0.01 mm and 0.4 mm, respectively (see bunch of ions in the center of the MT in Fig. 4). These steps were required to reduce a possible shift in the cyclotron-frequency ratio of the ^{123}Te$^+$ and ^{123}Sb$^+$ ions due to the anharmonicity of the trap potential and the inhomogeneity of the magnetic field to a level well below 10^{-10} [19]. After this preparatory step, the radius of the ion's cyclotron motion was increased to 0.5 mm in order to set the initial phase of the cyclotron motion (see off-axis bunches of ions in MT in Fig. 4). The ion's cyclotron frequency is alternately measured in the MT with the PI-ICR technique [18] by applying "measurement scheme 2" described in detail in [19]. After ejection from the MT, the phases of the radial ion motions are detected with a position-sensitive detector as shown on the right side of Fig. 4. The labels "ν_--" and "ν_+-phase" images indicate that during the phase accumulation time ions in the MT perform a magnetron and cyclotron motion, respectively. Since $\nu_+ \gg \nu_-$, the ν_+-phase spot is increased due to ion scattering on the residual gas, which in practice sets a limit to the maximum phase accumulation time of a few hundred milliseconds. A single phase measurement for a certain nuclide took a total measurement time of approximately 5 minutes. On this time scale the measurement of the phases of the radial motions can be considered to be performed simultaneously. Data with more than 5 detected ions per cycle were not taken into account in order to avoid a possible shift in the cyclotron-frequency ratio of the ^{123}Te$^+$ and ^{123}Sb$^+$ ions due to ion–ion interaction.

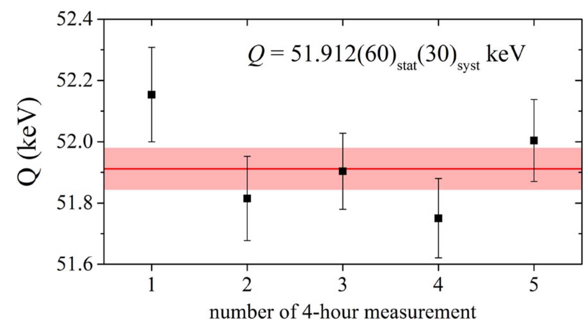

Fig. 5. The mass difference (Q-value) of ^{123}Te and ^{123}Sb calculated from the cyclotron-frequency ratios $R_{4-\text{hour}}$. The red line and the red shaded band are the average mass difference value and its statistical uncertainty. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In Fig. 5 the mass difference of ^{123}Te and ^{123}Sb calculated from the cyclotron-frequency ratios R is shown for the entire measurement period. During the measurement campaign five 4-hour measurements were performed and statistically averaged. For each measurement the ratio R_{4hour} of the cyclotron frequencies ν_c of the ^{123}Te$^+$ and ^{123}Sb$^+$ ions was obtained by polynomial fitting method [23]. The final frequency ratio R with its statistical and systematic uncertainties as well as the corresponding mass difference ΔM of ^{123}Te and ^{123}Sb are $R = 1.00000045344(52_{\text{stat}})(26_{\text{syst}})$ and $\Delta M = 51.912(60_{\text{stat}})(30_{\text{syst}})$ keV$/c^2$. The systematic uncertainty in the frequency-ratio determination originates from the anharmonicity of the trap potential, the inhomogeneity of the magnetic field, the distortion of the ion-motion projection onto the detector [19].

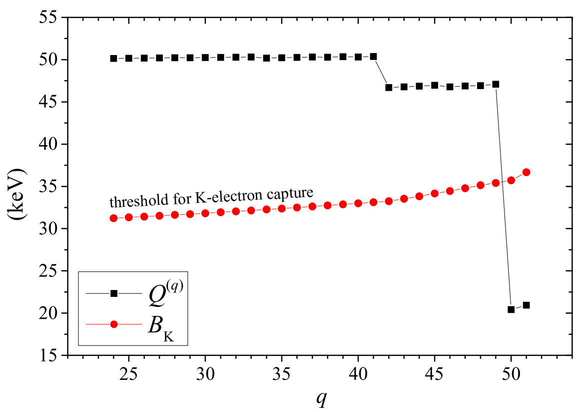

Fig. 6. Black squares: The mass difference $Q^{(q)}$ of $^{123}Te^{+q}(E^* = 159$ keV) and $^{123}Sb^{+q}(E^* = 160.3$ keV) ions according to Eq. (2); Red circles: K-electron binding energies in dependence on the qth ionic charge state. The uncertainty of all the values are well within the markers.

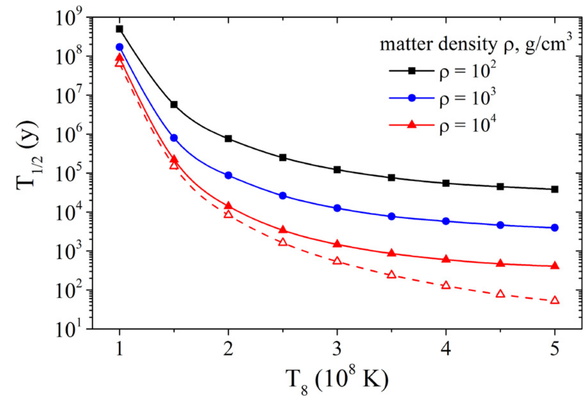

Fig. 7. Estimated half-lives for the allowed electron capture by the ^{123}Te excited state at 159 keV with the formalism of [15] in dependence on temperature in units of 10^8 K and on density in g/cm^3. The dashed curve shows the total half-lives which include the capture of free electrons for $\rho = 10^4$ g/cm^3.

4. Results and discussion

The measured Q-value of 51.912(67) keV (uncertainties added in square), confirms the AME value of 52.7(1.6) keV [9], but is about 40 times more precise. This value corresponds to the neutral atomic ground state mass difference of ^{123}Te and ^{123}Sb. Since in stellar conditions nuclear states are ionized one should determine the ionic mass values. This can be done for the ^{123}Te and ^{123}Sb nuclides applying:

$$Q^{(q)} = Q^{\text{neut}} + B^{\text{tot}}_{\text{Te}} - B^{\text{tot}}_{\text{Sb}} - B^{(52-q)}_{\text{Te}} + B^{(51-q)}_{\text{Sb}} + \\ + \epsilon^*_{\text{Te}} - \epsilon^*_{\text{Sb}} + E^*_{\text{Te}} - E^*_{\text{Sb}}, \quad (2)$$

where $Q^{(q)}$ is the mass difference for the qth ionic charge state of the $E^*_{\text{Te}} = 159$ keV and $E^*_{\text{Sb}} = 160.3$ keV levels, Q^{neut} is the neutral ground state mass difference value, ϵ^* is the energy of the excited atomic states, B^{tot} is the total electron binding energy, $B^{(52-q)}_{\text{Te}}$ and $B^{(51-q)}_{\text{Sb}}$ is the total binding energy of (52-q) and (51-q) electrons in Te^{+q} and Sb^{+q} ions, respectively. For the ionic states with charge numbers up to $q = 48^+$ the binding energies can be calculated using tabulated values [24], whereas for H- and He-like ions ($Te^{+50,+51}$, Sb^{+50}) they can be calculated by taking the tables of [25,26]. The least precise term in Eq. (2) is the Q^{neut} (± 67 eV), the precision of the first exited states of ^{123}Te and ^{123}Sb is 20 eV and 50 eV, respectively, and the most well-known values are the binding energies, which precision is better than a few eV.

In hot stellar conditions highly charged ions should predominantly be produced. Fig. 6 demonstrates various ionic mass differences of $^{123}Te^{+q}(E^* = 159$ keV) and $^{123}Sb^{+q}(E^* = 160.3$ keV) ions derived from Eq. (2) in dependence on the qth ionic charge state. Here we neglected the atomic excitation energy difference $\epsilon^*_{\text{Te}} - \epsilon^*_{\text{Sb}}$ and used for the electron binding energies the tabulated values of [24–26]. As an example, the ionic mass difference for the $q = 49^+$ ionic state is $Q^{(49)} = 47.1$ keV. However, for the $q = 50^+$ ionic state we obtain $Q^{(50)} = 20.4$ keV. From these examples we can conclude that the 49^+-state can decay via K-capture, whose electrons have a binding energy of 35.4 keV, whereas for ions with charge state $q = 50^+$ and 51^+ (H and He-like tellurium ions) the K-capture is energetically forbidden. These results as well as subsequent electron capture probability estimations strongly depend on the mass values of the neutral ground states, whose first direct and accurate measurement has been performed in this work. And if for example the Q^{neut}-value were only 30 keV, then all the $Q^{(q)}$-values (black squares) in Fig. 6 would be below the threshold for K-electron capture (red circles) what, in turn, can lead only to L,M,N-electron capture with smaller probabilities.

In high-temperature conditions (with $T = 1 \cdot 10^8 \sim 5 \cdot 10^8$ K) ionic states with different (including high) charges are produced. If the matter density exceeds 10^4 g/cm^3 the capture of free environmental electrons is highly probable. Detailed calculations of total decay rates of nuclides in high-temperature and high-density conditions have been done in [15]. The population of various ionic states in local thermal equilibrium has been calculated by using the Saha equation. With these assumptions and with the nuclear input data discussed here we have re-estimated the probabilities of the orbital as well as free electron capture by the nuclear excited states [15]. Fig. 7 depicts the dependence of the total effective half-life values on the temperature for the allowed capture process by the 159 keV excited state of ^{123}Te.

As can be seen in Fig. 7, the effective half-life of ^{123}Te in stellar conditions for a typical s-process temperature of $T \approx 3 \cdot 10^8$ K can reach the level of 10^3 y, which is more than fourteen orders of magnitude less than the expected terrestrial value of $> 10^{17}$ y. This dramatic enhancement of the decay probability of ^{123}Te in the stellar conditions could reveal an importance of this nuclide in understanding of the s-process scenarios. In particular, the temperature-dependent decay rates may set some meaningful constraints for the site(s) where this nuclide can be produced during the s-process. In massive stars the duration of the s-process is quite long and the strong electron capture can significantly influence the tellurium production mechanism. In the s-process in low-mass AGB stars, on the other hand, the duration of the high-temperature phase is very short, so that the opening of the ^{123}Te electron-capture channel will not significantly affect the production. An attempt to quantify these expectations has been made recently [27], which has analyzed the relative solar abundances of $^{122,123,124}Te$ in relation to the currently available astrophysical s-process scenarios. Indeed, it has shown that the proper consideration of the enhanced ^{123}Te electron-capture rates could set a stringent upper limit for the contribution to the solar abundances of those s-only isotopes from the s-process in massive stars.

5. Conclusion

The atomic mass difference of ^{123}Te and ^{123}Sb has been directly measured with the Penning-trap mass spectrometer SHIPTRAP. Cyclotron resonance frequencies have been measured using the phase-imaging ion-cyclotron-resonance detection method. The value of $Q = 51.912(67)$ keV was obtained for the mass difference. Based on reliable data the impact on the effective decay rate of ^{123}Te in stellar conditions has been investigated and revealed dramatic changes in electron capture probabilities of this pure s-process nuclide, which exceeds the terrestrial value by many orders of magnitude. Thus the terrestrially nearly stable nuclide ^{123}Te becomes radioactive in stars. This can lead to a depletion of ^{123}Te in the s-process nucleosynthesis.

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