The age of the Universe is one of the most important physical quantities in cosmology and it can be determined with the $r$-process nucleochronometer. Based on the classical $r$-process model, the $r$-process abundance patterns and various nuclear chronometers in the metal-poor halo stars are investigated by employing the newly developed nuclear mass models. It is found that the uncertainty of Th/Eu chronometer caused by nuclear mass uncertainties is about 4 Gyr, while the uncertainty of Th/Hf chronometer is so large that it should be taken with caution. With the Th/Eu chronometer, the age of the metal-poor stars CS 31082-001 is determined as $16.3 \pm 7.1$ Gyr, which agrees well with the results derived from Th/U chronometer.

Keywords: nuclear chronometer; $r$-process; metal-poor star.

1. Introduction

The age of the Universe is one of the most important physical quantities in cosmology. As the metal-poor stars were formed at the early epoch of the Universe, their ages can set a lower limit on the age of the Universe. The ages of these stars can be determined by nuclear chronometers, which rely on the comparison of the present abundances of radioactive nuclei with the initial abundances at their productions.

The initial abundance of these radioactive nuclei can be derived from $r$-process calculations. However, most of neutron-rich nuclei of relevance
to the $r$-process are not accessible in experiments, consequently, $r$-process calculations crucially depend on accurate theoretical predictions for nuclear masses, $\beta$-decay half-lives, etc. Therefore, it is necessary to make a systematic investigation of the uncertainties of age estimate using nuclear masses. During the past decades, a number of investigations in $r$-process chronometers have been reported in literatures based on a few widely used mass models, such as finite-range droplet model (FRDM). Recently, many mass models, such as Duflo-Zuker DZ31, Hartree-Fock-Bogoliubov (HFB-17), relativistic mean field (RMF), and an improved macroscopic-microscopic mass formula with Woods-Saxon potential (WS*), are developed. Although these newly developed mass models can well reproduce the experimental data, they are not included in the previous analysis of the nuclear chronometer. In Ref. 10, the influence of nuclear masses on Th/U chronometer is investigated with the newly developed mass models. However, the U lines were only detected in three metal-poor stars CS 31082-001, BD +17$^\circ$3248, and HE 1523-0901. Therefore, it is necessary to investigate the uncertainty of Th/X (X represents a stable element) chronometers, especially the commonly used Th/Eu and recently proposed Th/Hf chronometers, using the nuclear mass predictions from these newly developed models.

In this work, we will analyze the abundance pattern of metal-poor star and deduce its age with the Th/Eu and Th/Hf chronometers. The improved nuclear mass models have been used in our $r$-process calculations. In Sec. 2, a brief introduction to the classical $r$-process model and the nuclear physics inputs used in this work are given. In Sec. 3, the influence of nuclear masses on the $r$-process calculations and the age estimate of the metal-poor star are discussed. Finally, a summary is presented in Sec. 4.

2. Sketch of the classical $r$-process model

The classical $r$-process model is adopted in this investigation to deduce the initial Th/Eu and Th/Hf abundance ratios as in Refs. 1,3,10. In this model, seed-nuclei (iron) are irradiated by neutron sources of high and continuous neutron densities $n_n$ over a timescale $\tau$ in a high temperature environment ($T \sim 1$ GK). A configuration of sixteen $r$-process components with neutron densities in the range of $10^{20}$ to $3 \times 10^{27}$ cm$^{-3}$ is chosen to reproduce the solar $r$-process abundances. This model is considered as a realistic simplification of dynamical $r$-process model, and it has been successfully employed in describing $r$-process patterns of both the Solar System and metal-poor stars.
In this work, available experimental data\textsuperscript{20,21} are used, otherwise predictions of mass models DZ10\textsuperscript{22} DZ31,\textsuperscript{6} FRDM,\textsuperscript{5} HFB-17,\textsuperscript{7} RMF,\textsuperscript{8} and WS*\textsuperscript{9} are employed. As for the $\beta$-decay rates, the predictions of the FRDM+quasiparticle random-phase approximation (QRPA) method\textsuperscript{23} are employed throughout the paper as a complement to the experimental data\textsuperscript{20}.

3. Results and Discussions

3.1. The Influence of Mass Models

The $r$-process calculations using various nuclear mass models can yield abundances differing even by several orders of magnitude.\textsuperscript{15} It is therefore necessary to test their reliability before applying them to age estimates. In Fig. 1, the $r$-process simulations for DZ10, DZ31, FRDM, WS*, HFB-17, and RMF mass models are shown and compared with the observations. In the whole region of $38 \leq Z \leq 82$, the simulation using the DZ31 mass model better reproduce observations and the rms value with respect to observation is approximately 0.34, while the simulation using the RMF mass model has larger deviations for the heavier neutron-capture nuclei ($Z > 56$) and the rms value with respect to observations is 0.52. For the simulations using other mass models, the corresponding rms values are in between.

Since the elements Eu ($Z = 63$) and Hf ($Z = 72$) locate in the region $56 \leq Z \leq 82$, it is essential to well reproduce the observations in this region for the Th/Eu and Th/Hf chronometers. From Fig. 1, it is found that the simulations using the DZ10, WS*, DZ31, FRDM mass models better reproduce observations, and the rms values with respect to observations are 0.25, 0.31, 0.33, 0.38, respectively. Due to the large trough around $Z \sim 70$, the rms values increase to 0.48 and 0.58 for the simulations using HFB-17 and RMF mass models. This large trough might be due to the large neutron shell gap, which has not been well understood at present. Consequently, the abundances of Hf are underestimated for the simulations using HFB-17 and RMF mass models. Meanwhile, the underestimation of Hf abundance is also observed for the FRDM simulation, although the trough around $Z \sim 70$ is smaller for this simulation. This underestimation can lead to large scattering of Th/Hf abundance ratio, hence the age estimated from Th/Hf chronometer, when different mass models are employed for the $r$-process calculations.
Fig. 1. Calculated $r$-process abundances (scaled to Eu) using various mass models. The filled circles represent the scaled average element abundances of CS 31082-001 and CS 22892-052 in the region $Z < 82$. The abundances for Pb, Th and the upper limit (open circle) on U are taken from CS 22892-052. We adopt the usual notation that $\log_{10}(\epsilon(A)) = \log_{10}(N_A/N_H) + 12.0$ for element A, where $N$ represents abundance.

3.2. Age Estimates from Th/Eu and Th/Hf Chronometers

With the initial $r$-process abundance ratios Th/Eu and Th/Hf and their present observed values, one can eventually deduce the age of the metal-poor star. In Fig. 2, the ages of the metal-poor star CS 31082-001 are presented for different chronometers. For the Th/Eu chronometer, the left panel of Fig. 2, the ages determined using DZ10 and DZ31 mass models are similar, while the ages estimated using other mass models are slightly longer. Considering the errors from observations, all results using Th/Eu chronometer are agreement with each other. However, it is different for the Th/Hf chronometer. From the right panel of Fig. 2, it is found that the ages determined using FRDM, HFB-17, and RMF mass models are so large that they cannot be consistent with the ages determined using DZ10 and DZ31 mass models. This deviation can be traced back to the large scattering of Th/Hf abundance (refer to Fig. 1). This might imply that the age estimate using Th/Hf chronometer should be taken with caution.

In order to estimate the age of a star more reliably, one could adopt the average values for different simulations. The corresponding uncertainty
Fig. 2. Age of the metal-poor star CS 31082-001 determined using Th/Eu (left panel) and Th/Hf (right panel) chronometers. For each panel, the first six circles from the left to right represent the ages estimated using DZ10, DZ31, FRDM, HFB-17, RMF, and WS* mass models, respectively, while the last two circles denote the average ages with all mass models and the four mass models DZ10, DZ31, FRDM, and WS*. The shaded areas correspond to the age determined using the Th/U chronometer from Ref. 10.

is their root mean square deviation. From the above discussion, it is clear that the DZ10, DZ31, KTUY, and WS* simulations reproduce the stable element abundances better than the others. Therefore, these mass models might be more credible and are selected to estimate the age of a metal-poor star. For the Th/Eu chronometer, the age of metal-poor star CS 31082-001 is obtained as $16.3 \pm 7.1$ Gyr, which agrees with the value of $13.5$ Gyr determined using Th/U chronometer in Ref. 10. The uncertainty of age determined here includes that of $4.3$ Gyr from nuclear mass models and $5.6$ Gyr from observation. Similarly, the age of CS 31082-001 from Th/Hf chronometer is deduced as $25.5 \pm 14.7$ Gyr. For comparison, the corresponding average ages for all the mass models using the Th/Eu and Th/Hf chronometers are determined as $17.2 \pm 6.8$ and $29.3 \pm 13.8$ Gyr with uncertainties of $3.6$ and $11.3$ Gyr from nuclear mass models, respectively. At last, it should point out that results calculated from Th/Hf chronometer should be taken with caution due to the large uncertainties of Th/Hf abundance ratio from nuclear masses.

4. Summary

In this work, the r-process abundance pattern in metal-poor star and the ages estimated using Th/Eu and Th/Hf chronometers have been investigated. It is found that the uncertainty of Th/Eu chronometer from nuclear masses is about $4$ Gyr, while the uncertainty of Th/Hf chronometer is so large that it should be taken with caution. By adopting the Th/Eu chronometer, the age of the metal-poor stars CS 31082-001 is determined
as 16.3 ± 7.1 Gyr with the uncertainty of 4.3 Gyr from nuclear masses. This result agrees well with the results derived from Th/U chronometer. In order to reduce the age uncertainty in present work, it is essential to develop more reliable nuclear models and make more precise observations from metal-poor stars.

5. Acknowledgments

This work is partly supported by Major State 973 Program 2007CB815000 and the NSFC under Grant Nos. 10947013, 10947149 and 10975008, the NCET, and the Fundamental Research Funds for the Central Universities.

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