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Systematic Studies on the β-decay Half-lives of r-process Nuclei

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Abstract. Based on the accurate macroscopic-microscopic mass formula and the experimental data of β-decay half-lives of the nuclei with atomic number ranging from 20 to 190, a systematic formula has been proposed to calculate β-decay half-lives of neutron-rich nuclei. The formula is proved to reproduce the experimental β-decay half-lives of neutron-rich nuclei very well, and then is used to study the r-process nucleosynthesis in models of high-entropy mass outflows. The calculated abundances show a good agreement with the solar r-abundances around the third peak and the rare earth mass region.

1 Introduction

The rapid neutron-capture process (r-process) of stellar nucleosynthesis is believed to explain the production of about half of the nuclides heavier than iron in the universe [1, 2]. A large amount of nuclear data, such as mass, decay and reaction rates, are necessary in the studies of r-process. Among them, the β-decay half-lives of a large range of extremely neutron-rich nuclei are one of the most important inputs in the r-process model calculations. However, for the lack of experimental data, the identification of the realistic site and the exact path of the r-process has proved to be very difficult.

In this work, we have systematically investigated the variation of β-decay half-lives with the decay energy Q and nucleon number (Z, N) based on the experimental data. A systematic formula has been proposed to calculate the β-decay half-lives of that neutron-rich nuclei after taking into account the shell effects and pairing effects. The formula is tested for the resent experimental data, and then used to predict the β-decay half-lives of some nuclei far from stability including the ones on the possible r-process path.

2 Systematic formula for β-decay half-lives

According to Fermi's golden rule [3], the decay constant (or transition probability) of β-decay is defined by

$$\lambda = \frac{ln2}{T_{1/2}} = \frac{m_e^5 c^4 g^2 |M_{if}|^2}{2\pi^3 \hbar^7} f(Z, E_m). \tag{1}$$

To obtain the decay constant, the transition matrix element M_{if} and phase-space factor $f(Z, E_m)$ should be worked out firstly. $f(Z, E_m)$ is a function of the radius of the nucleus R =

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$r_0 A^{1/3}$, nuclear charge Z, and the energies of the emitted electron E_e. A formula for β-decay half-lives $\ln(T_{1/2})$ should include these three terms: $\alpha^2 Z^2 \ln(2R)$, $(\alpha^2 Z^2 - 5)\ln Q$ and $-\alpha Z\pi$. The term $(\alpha^2 Z^2 - 5)\ln Q$ is essential for the generalized Sargent law. The atomic masses are the key values to calculate Q-values, thus we select the very recent atomic mass table given by Wang [4] as our input data. The deviations between experimental and calculated Q-values are about 5%.

The nuclear matrix element contains the information of nuclear structure, the shell effects and pairing effects. The pairing effects on β-decay half-lives versus Q-values can be well described by Eq. (2).

$$\delta = (-1)^N + (-1)^Z. \tag{2}$$

The shell effects become strong near the neutron and proton magic-numbers, which can be well characterized by

$$\begin{aligned} S(Z,N) =& a_1 e^{-\frac{(N-28)^2+(Z-20)^2}{12}} + a_2 e^{-\frac{(N-50)^2+(Z-38)^2}{43}} + a_3 e^{-\frac{(N-82)^2+(Z-50)^2}{13}} \\ &+ a_4 e^{-\frac{(N-82)^2+(Z-58)^2}{24}} + a_5 e^{-\frac{(N-110)^2+(Z-70)^2}{244}}. \end{aligned} \tag{3}$$

It must be pointed out that a complete correction of shell effects should include all major shell as well as sub-shell closures. However, when taking account of the range of available experimental data, only portions of magic-numbers which have the most remarkable effects are included in Eq. (3).

Consequently, a systematic formula for β-decay half-lives of neuron-rich nuclei far from stability line can be derived from the relationship between β-decay half-lives and Q-values, nucleon numbers (Z,N), neutron excess $(N - Z)/A$, with corrections of pairing effects and shell effects. The new formula is expressed as

$$\begin{aligned} \ln(T_{1/2}) =& a_6 + (\alpha^2 Z^2 - 5 - a_7 \frac{N-Z}{A}) \ln(Q - a_8\delta) + a_9 \alpha^2 Z^2 \\ &+ \frac{1}{3}\alpha^2 Z^2 \ln A - \alpha Z\pi + S(Z,N), \end{aligned} \tag{4}$$

with the parameters $a_i (i = 1, 2, \cdots, 9)$ determined according to all available experimental data of β-decay half-lives of nuclei far from stability line ($\delta N > 5$). The most important term $(\alpha^2 Z^2 - 5 - a_7 \frac{N-Z}{A}) \ln(Q - a_8\delta)$ has a vital effect on the calculation of β-decay half-lives. The latter three terms in Eq. (4) have relatively small contribution to the total value and have minor fluctuation versus (Z, N). As for the shell correction $S(Z,N)$, it has obvious contribution only near the nucleon magic-numbers but contributes nothing far from nucleon magic-numbers.

Through a least-square fitting to all available experimental data of 350 nuclei far from the β-stability line, we obtain all parameters in Eq. (4): $a_i (i = 1, 2, \cdots, 9)$ = 3.016, 3.879, 1.322, 6.030, 1.669, 11.09, 1.07, -0.935, -5.398, respectively. The average ratio between calculated β-decay half-lives and experimental ones is about 1.69. It reproduces 308 (88%) nuclei of 350 available experimental data within a factor of 3, and 261 (74.6%) nuclei within a factor of 2. To demonstrate the extrapolating capacity of the systematic formula, we have also calculated the β-decay half-lives of the isotopic chains such as Zr, Rb, Sr, Y and compare them with the experimental data [5]. The results are shown in Fig. 1. One can see that the agreements are very well. The ratios between calculated β-decay half-lives and experimental ones of these 17 nuclei are within a factor of 1.15. It is interesting to see from Fig. 1 that extrapolations of these isotopic chains have smaller deviations than the other reproduced β-decay half-lives.

The half-lives deduced with the current systematic formula has been used to study the r-process nucleosynthesis in models of high-entropy mass outflows. The calculated abundances show a good agreement with the solar r-abundances around the third peak and the rare earth mass region.

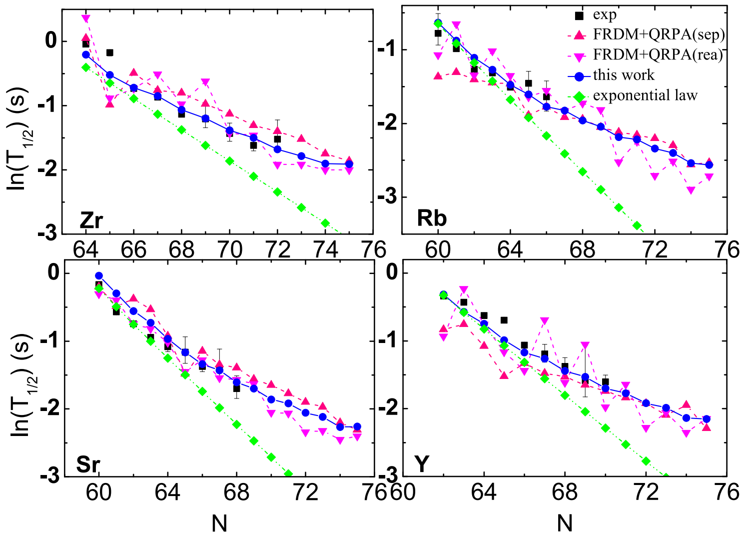

Figure 1. (Color online)A comparison among the calculated logarithm of half-lives from the exponential law [6] (diamonds), this work (dots), microscopic approaches [7, 8] (triangles) and measured ones [5] for Zr, Rb, Sr, Y isotopes.

3 Summary

Based on the Fermi's theory of β-decay and experimental data, the variation of β-decay half-lives with the decay energy Q and nucleon number (Z, N) has been systematically investigated. A empirical formula has been proposed for the calculation of β-decay half-lives of neutron-rich nuclei. The present formula works well in extrapolating the experimentally unknown r-process nuclei and in the model calculations of r-process nucleosynthesis.

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