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Modern Results for the Cosmic Ray Nucleosynthesis of *p*-Nuclei

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Significantly improved results of the cosmic ray nucleosynthesis (CRN) of proton-rich stable nuclides (*p*-nuclides) are obtained based upon a detailed treatment of the cosmic ray (CR) nuclear transport including the spallation, decay, energy loss, and escape from the Galaxy. Latest nuclear data are compiled, and the latest semi-empirical formulae SPACS are adopted for the spallation cross sections. Effective electron-capture decay rates are calculated using proper cross sections for recombination and ionization in the whole CR energy region. Abundances of proton-rich unstable nuclides increase in CRs with increasing energy relative to those of other nuclides since the electron-capture decay is hindered by the ionization. We derive yields of the primary and secondary spallation processes and differential yields from respective seed nuclides. It is shown that the CR energy region of $\leq O(100)$ MeV/nucleon predominantly contributes to the total yields. Therefore, atomic cross sections in the low-energy range should be input accurately. We identify important seed nuclides for all *p*-nuclides. The contribution of CRN is significant only for ^{180m}Ta, which accounts for about 20 % of the solar abundance. CRN yields of other *p*-nuclides are typically about $O(10^{-4}$–$10^{-2})$ of solar abundances.

KEYWORDS: atomic processes, cosmic rays, nucleosynthesis, solar abundances

1. Introduction

The *p*-nuclides are stable nuclides with atomic numbers $Z \geq 34$ on the proton-rich side of the β-stability line [1]. They are thermally produced at temperatures $T = (2$–$3) \times 10^9$ K via the proton capture and photodisintegration reactions [2]. The photodisintegration occurs in the O-Ne rich layers of massive stars during core-collapse supernovae (SNe), i.e., SN II, SN Ib, SN Ic [3, 4]. The *p*-nuclei are also produced in the outermost layers of an exploding carbon-oxygen white dwarf thought to be a SN Ia [5, 6]. Although there is a large uncertainty in the abundances of the *s*-nuclei produced prior to SN Ia, SNe Ia can produce abundant *p*-nuclei consistent with their solar abundances [6]. This contribution explains significant underproduction of *p*-nuclides in SNe II relative to the solar abundances [4].

In cosmic ray (CR) nucleosynthesis, there are two components: the primary process between heavy CR nuclides and protons (or ^{4}He nuclei) in the interstellar medium (ISM), i.e., $A_{\rm CR} + (p\alpha)_{\rm ISM}$; and the secondary process between protons (or ^{4}He nuclei) in CRs and heavy nuclides in the ISM, i.e., $(p\alpha)_{\rm CR} + A_{\rm ISM}$. The CR nucleosynthesis (CRN) of *p*-nuclides has been studied, and yields have been estimated [7]. In that work the yields were generally a small fraction $O(10^{-3} - 10^{-2})$ of the solar abundances, although the yields of four heavy *p*-nuclides, i.e., ^{180m}Ta, ^{184}Os, ^{190}Pt, and ^{196}Hg, were found to be 13 to 70 percent of the solar abundances.

The propagation of heavy CR nuclides up to $Z = 83$ have been investigated for energies above a few hundred MeV per nucleon [8]. High energy CRs are typically ionized, and their electron capture decays are hindered. In calculations of CR transfer, therefore, the fraction of the bound states of nuclei with electrons must be taken into account [8, 9].

For nuclear spallation cross sections, semi-empirical formulae have been developed and used in CR studies. Charge distributions for spallation residue nuclides have been measured for many target nuclides by proton collision, and their results are described by semi-empirical formulae.

In this paper, we show results of a detailed calculation of the CRN of p-nuclides [10] which takes into account: (1) the dependence of the spallation cross section on the collision energy; and (2) the survival probability of the CR nuclides. We adopt results of CR compositions from satellite observations, and the latest formulae for the spallation cross sections. This result is then used to predict the yields of p-nuclides for a standard CRN model.

2. Model

2.1 Cosmic ray transfer

We adopt the transport equation of CRs given [11] by

$$\begin{aligned}\frac{\partial J_i(E)}{\partial X} &= \frac{Q_i(E)}{\rho} - r_{\mathrm{e}}(E)_i J_i(E) + \frac{\partial}{\partial E}\left[W_i(E)J_i(E)\right] - r_{\mathrm{spa},i}(E)J_i(E) \\ &\quad + \sum_j r_{\mathrm{spa},ij}(E)J_j(E) - \sum_m \left[r^m_{\mathrm{d},i}(E)g^m_i(E)\right] J_i(E) + \sum_{j,m}\left[r^m_{\mathrm{d},ij}(E)g^m_j(E)\right] J_j(E). \qquad (1)\end{aligned}$$

Here $J_i(E)$ is the flux of CR nuclide i [cm^{-2} s^{-1} (MeV/A)$^{-1}$] as a function of kinetic energy E (MeV/A), $X \equiv \rho v t$ (g cm^{-2}) with ρ the density (g cm^{-3}) and v the velocity (cm/s), $Q(E)$ is the injection rate (particles cm^{-3} s^{-1} (MeV/A)$^{-1}$), r_{e} is the escape rate (cm^2 g^{-1}), W is the stopping power (MeV/A cm^2 g^{-1}). A nuclear reaction network is constructed in the mass range of $A = [74, 209]$, and steady-state solutions for this set of equations are derived.

2.2 Inputs from observations and experiments

The CR injection spectrum of species i is given by a power-law in momentum p (in MeV/A). Elemental compositions of CR heavy nuclides are taken from various measurements (references in Ref. [10]). In the network calculation, the $\beta^{\pm}$, electron-capture, α-, and isomeric-transition decays of radioactive nuclei are taken into account. Nuclear data from the BNL (2011) compilation and ENSDF[1] are adopted.

2.3 Theoretical inputs

A semi-empirical parameterization for the isotopic spallation cross sections for nucleon collision, i.e. the SPACS [12] was adopted. CR ultraheavy nuclides with $Z > 28$ at $E \sim 1$ GeV have relatively large fractions of bound electron. The effective electron capture decay rate is therefore not significantly hindered, and the fractions of nuclei with a k-shell electron must be taken into account [8, 9, 11]. The production of p-nuclei in CRN predominantly occurs in the low energy region of $E \leq O(100)$ MeV/nucleon [10]. Therefore, accurate atomic cross sections must be utilized to derive ionization degrees of CR nuclei for CRN calculations.

Table I shows theoretical models of atomic cross sections adopted in the current work.

3. Results

Figure 1 shows the new and old rates for radiative and nonradiative recombinations and electron stripping as a function of energy for $Z_{\mathrm{proj}} = 82$. All rates adopted in previous studies [8, 9] signifi-

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[1] http://www.nndc.bnl.gov/ensdf

Table I. Adopted atomic cross sections.

	Radiative recombination	Collisional recombination	Electron stripping
$v/c < 0.9$	Relativistic [13]	Eikonal approx. [14]	Boron approx. [15]
$v/c \geq 0.9$	1st Born+Oppenheimer [8]	Eikonal approx. [14]	Independent scattering approx. [16]

cantly deviate from the more accurate new rates at nonrelativistic energies $E \lesssim 1$ GeV/A. This figure illustrates the importance of using accurate cross sections in the low energy region.

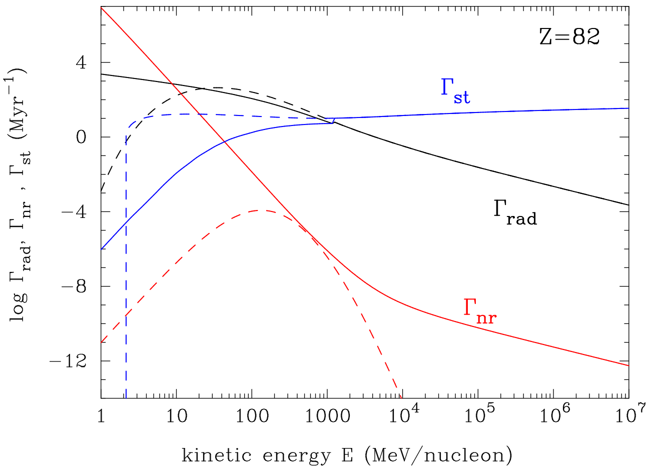

Fig. 1. New (solid lines) and previous (dashed lines) rates of the radiative and nonradiative recombinations and electron stripping, $\Gamma_{\rm rad}$, $\Gamma_{\rm nr}$, $\Gamma_{\rm st}$, respectively, versus energy for $Z_{\rm proj} = 82$. Reprinted from Ref. [10].

Figure 2 (left panel) shows the CRN yields and the solar abundances of p-nuclides (upper subpanel) and their ratios (lower subpanel). The contribution of CRN to the solar abundances of p-nuclides is small in general. However, $\sim$ 20 % of the solar system ^{180m}Ta is produced from CRN. Figure 2 (right panel) shows the separated CRN yields of the primary and the secondary processes.

Figure 3 (left panel) shows the calculated CRN yields and the solar abundances of Fe-peak nuclei (upper subpanel) and their ratios (lower subpanel). CRN only significantly contributes to the Galactic chemical evolution of ^{50}V. We find that $\sim$ 35 % of the solar system ^{50}V is produced from CRN. Figure 3 (right panel) shows the fractions for contributions of the primary and secondary processes to the ^{50}V production. Seed nuclei with larger solar abundances mainly contribute to the CRN yield of ^{50}V more.

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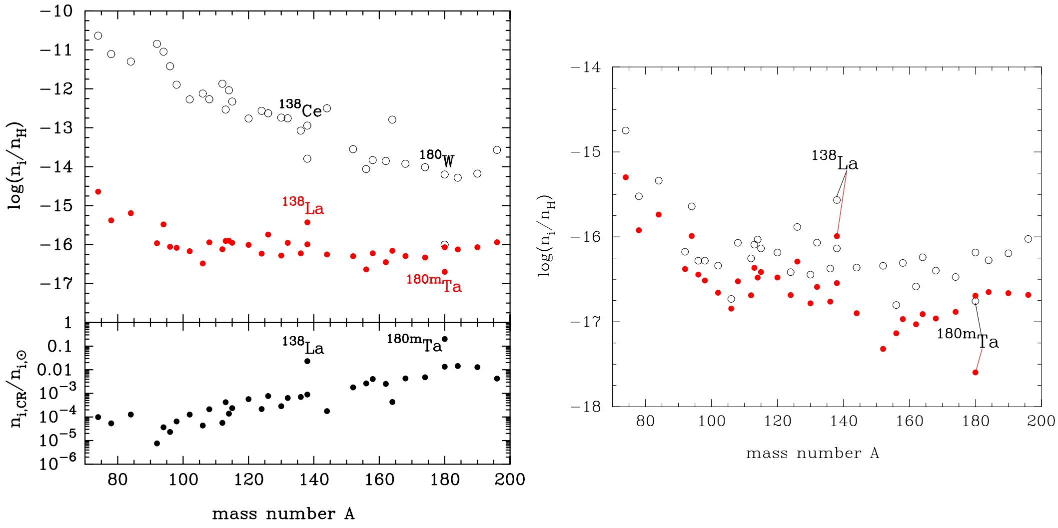

Fig. 2. (left panel) CRN yields (sold circles) and the solar system abundances (open circles) of *p*-nuclides (upper subpanel) and their ratios (lower subpanel) as a function of mass number; (right panel) separated yields of the primary (open circles) and the secondary (solid circles) processes as a function of mass number. Reprinted from Ref. [10].

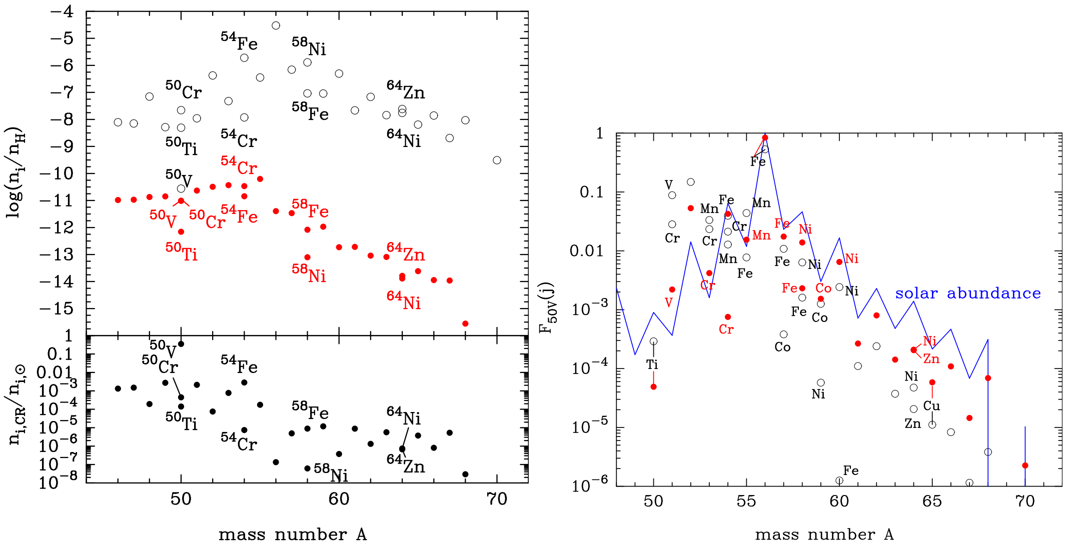

Fig. 3. (left panel) CRN yields (solid circles) and the solar system abundances (open circles) of Fe-peak nuclei (upper subpanel) and their ratios (lower subpanel) as a function of mass number; (right panel) Fractions of ^{50}V yields of the primary (open circles) and secondary processes (solid circles), respectively, from the seed nuclide j as a function of mass number of j. The solid line shows the solar abundance normalized to the ^{56}Fe abundance. Reprinted from Ref. [10].

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