Applied Radiation and Isotopes 105 (2015) 114–118

Contents lists available at ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Decay data of radionuclides along the valley of nuclear stability for astrophysical applications

Valery P. Chechev [a,*], Xiaolong Huang [b]

[a] V.G. Khlopin Radium Institute, 194021 Saint Petersburg, Russia
[b] China Institute of Atomic Energy, P.O. Box 275(41), Beijing 102413, China

HIGHLIGHTS

- We consider radionuclides along the valley of nuclear stability.
- Some demands for their decay data in astrophysics are discussed.
- Half-lives and γ-ray intensities are recommended for 10 radionuclides.
- List of radionuclides is offered for their nuclear characteristics to be evaluated.

ARTICLE INFO

Article history:
Received 12 January 2015
Received in revised form
1 July 2015
Accepted 14 July 2015
Available online 21 July 2015

Keywords:
Radionuclides
Decay data
Half-life
γ-rays
Nucleosynthesis
s-process

ABSTRACT

Several directions of the demand for decay data in nuclear astrophysics are discussed for radionuclides near the valley of nuclear stability. The current half-life and gamma-ray intensity evaluation results are presented for some radionuclides of astrophysical interest. An extended list of such nuclides is offered for their nuclear characteristics to be further evaluated by the Decay Data Evaluation Project collaboration participants.

1. Introduction

For radionuclide decay data, at present there are available two sources of high-quality evaluated information for users: ENSDF and DDEP data. All other datasets are abstracted from some combination of these data sources. The ENSDF comprehensive data cover all known radionuclides but have a disadvantage of very unequal (sometimes old) dating of evaluations for radionuclides with different mass numbers (A). From the viewpoint of simultaneous data selection for a specific group of nuclides having different A, for example, gamma ray standards, dosimetry reaction residuals, medical isotopes, etc., the DDEP data are more attractive for users. The Decay Data Evaluation Project (DDEP) collaboration has aimed at the applied radionuclides (Helmer et al., 2002; Bé and Chechev, 2013) all of which are located along the valley of nuclear stability. For such nuclides, there are available usually several measurement results for the same decay characteristics, often discrepant. Consequently, these characteristics are in greater need of more detailed evaluation using a user-proven technology such as particularly adopted by the working group of the DDEP cooperation.

In this paper we want to specify some groups of radionuclides along the valley of nuclear stability, decay data of which are used in nuclear astrophysics, geochronology and cosmochronology and which could be proposed for inclusion in the list of DDEP nuclides to evaluate their decay characteristics. Also we have evaluated some of them using the approaches and methodology adopted by the DDEP collaboration.

An important task is a detailed consideration of the improved decay data impact on the astrophysical conclusions that is not the purpose of this paper. It is a subject of some previous (e.g., Begemann et al., 2001; Rugel et al., 2009) and future works. In any case, we believe, regardless of the significance of such effect, it would be

* Corresponding author. Fax.: +7 812 2978095.
E-mail address: chechev@khlopin.ru (V.P. Chechev).

http://dx.doi.org/10.1016/j.apradiso.2015.07.018
0969-8043/

beneficial to use the current updated evaluated decay data not only in applied physics but also in nuclear astrophysics and cosmological dating.

2. Half-lives of long-lived radionuclides

The first direction of the demand for decay characteristics in nuclear astrophysics and especially in geo- and cosmochronology is associated with half-lives of long-lived radionuclides ($T_{1/2} > 10^8$ years) such as ^{40}K, ^{87}Rb, ^{176}Lu, ^{187}Re, ^{232}Th, ^{235}U, and ^{238}U. Another group includes relatively short-lived radionuclides (10^5 yr $< T_{1/2} < 10^8$ yr), now extinct, decay of which after the solidification of the planetary and meteoritic material provides information about the details of nucleosynthesis in the early history of the solar system (Wasserburg and Papanastassiou, 1982). These are ^{26}Al, ^{53}Mn, ^{60}Fe, ^{93}Zr, ^{98}Tc, ^{107}Pd, ^{129}I, ^{135}Cs, ^{146}Sm, ^{182}Hf, ^{205}Pb, ^{244}Pu, and ^{247}Cm (Chechev, 2011).

Nuclear geochronology and cosmochronology using independence of the radioactive decay rate on the external conditions can determine an age of the objects which contain long-lived radioactive nuclides and/or their daughter products. Since such determination of the age of minerals is based on accurate mass spectrometric measurements of the relative concentration of isotopes, in recent years in geochronology it was found that the accuracy of the radioisotope ages of minerals is limited by the accuracy of radioactive decay constants (Begemann et al., 2001). Therefore to analyze this situation, the current evaluated half-life values must be available.

A summary of recommended (evaluated) half-life values was given for all the above 20 radionuclides by Chechev (2011) with detailed consideration of earlier experimental data and evaluations in (Chechev, 2001). To date, due to the publication of more accurate measurements (Rugel et al., 2009; Cassette et al., 2010; Kossert et al., 2013; Hult et al., 2014), the recommended half-life values should be changed for ^{60}Fe, ^{93}Zr and ^{176}Lu.

A new determination of the half-life of ^{60}Fe using high precision measurements of the number of atoms and their activity in a sample containing over 10^{15} atoms of ^{60}Fe (Rugel et al., 2009) gave the ^{60}Fe half-life value of $(2.62 \pm 0.04) \times 10^6$ yr, significantly above the previously reported value of $(1.49 \pm 0.27) \times 10^6$ yr (Kutschera et al., 1984). This new result of 2.62 (4) million years can be considered as the current recommended half-life of ^{60}Fe for astrophysical applications (Browne and Tuli, 2013). In particular, this value leads to lower estimate of a supernova deposit of ^{60}Fe on the Solar system and assumption of more distant source of its origin (Rugel et al., 2009).

For the half-life of ^{93}Zr, we have adopted the DDEP evaluation by Kellett (2013) which takes into account the recent measurement result of $(1.64 \pm 0.06) \times 10^6$ yr (Cassette et al., 2010). Thus, the recommended ^{93}Zr half-life is 1.61 (6) million years obtained as the weighted mean of the values of (Cassette et al., 2010) and $(1.53 \pm 0.10) \times 10^6$ yr from (Flynn, 1972). The lower uncertainty given by Cassette et al. (2010) was adopted for the recommended value.

For the half-life of ^{176}Lu, we revised the previous evaluation of $3.76\ (8) \times 10^{10}$ yr (Chechev, 2011) taking into account additionally the two recent measurement results of $(3.640 \pm 0.035) \times 10^{10}$ yr (Kossert et al., 2013) and $(3.722 \pm 0.029) \times 10^{10}$ yr (Hult et al., 2014). The overview of all the available ^{176}Lu half-life values reported in the literature is given in (Hult et al., 2014). Our statistical processing of this set was carried out with the LWEIGHT computer program using the limitation of relative statistical weight method (LWM) (Browne, 1998; Bé and Chechev, 2013). Thus, the current (updated) recommended value of the ^{176}Lu half-life is $3.72\ (6) \times 10^{10}$ yr.

In conclusion of this section it should be noted that there are still only the early half-life measurements for ^{98}Tc, ^{107}Pd and ^{205}Pb, and new measurements are needed for them. Also new precise measurements would be beneficial for the half-lives of the important cosmocronometers ^{235}U and ^{238}U as geo- and cosmochronological outputs based on their decay constants use the single accurate measurement by Jaffey et al. (1971).

3. Radionuclides the decays of which generate gamma-rays observed by orbital detectors

The second direction of astrophysical interest includes decay data, mainly γ-ray characteristics for radionuclides the decays of which generate gamma-rays observed (or which can be observed) by orbital observatories such as INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) and Fermi Gamma-ray Space Telescope (GLAST). Radioactive isotopes are co-produced with stable isotopes in stellar interiors, supernovae, novae, and interstellar space. Stellar interiors are opaque, but expanding explosive sites of nucleosynthesis such as novae and supernovae are gamma-ray transparent typically a few days to weeks after the explosion, thus allowing a direct gamma-ray view at the nucleosynthesis site. Only a small number of isotopes produced in nucleosynthesis in significant quantity have half-lives sufficiently long to remain undecayed before transparency of the site: ^{7}Be, ^{22}Na, ^{26}Al, ^{44}Ti, ^{56}Ni, ^{57}Co, and ^{60}Fe (Diehl et al., 2006). Below we have given the recommended (evaluated) values of main decay characteristics for these radionuclides and their daughters along with the relevant references to the cited evaluations (Table 1). γ-ray characteristics are presented in the fourth column of the table: the evaluated energies ($E\gamma$, keV) and absolute intensities per 100 decays ($I\gamma$, %) of prominent γ-rays.

We have updated the evaluated data for some decay characteristics mentioned in footnotes at the bottom of Table 1. Small changes in gamma-ray intensities for ^{44}Ti/^{44}Sc, ^{57}Co, ^{60}Co compared to those from earlier DDEP evaluations are due to using new theoretical ICC (Kibèdi et al., 2008). For the half-life of ^{7}Be, taking into account the new measurement results from (Mazzocchi et al., 2012) in addition to the 12 experimental values used in the evaluation by Helmer and Schönfeld (2004) changes slightly the recommended value from 53.22 (6) d to 53.23 (4) d. For the half-lives of ^{22}Na, ^{57}Co and ^{60}Co, the 2014 corrected NIST values (Unterweger and Fitzgerald, 2014) were introduced into the available experimental data sets instead of their previously reported results, and the recommended values have been changed compared to earlier DDEP evaluations from 2.6029 (8) yr by Galán (2009) to the current value of 2.6020 (4) yr for ^{22}Na, from 271.80 (5) d (Chechev et al., 2004) to 271.81 (4) d for ^{57}Co and from 5.2711 (8) yr (Helmer, 2006) to 5.2710 (8) yr for ^{60}Co.

It should be noted that small differences in $T_{1/2}$ and Iγ obtained in this evaluation with respect to earlier DDEP results have no effect on astrophysical conclusions, but to calibrate the gamma-ray detectors placed on satellites, in all cases, the current updated evaluated data must be used.

The re-evaluated data were obtained using the approaches and methodology adopted by the working group of the DDEP collaboration (Helmer et al., 2002; Bé and Chechev, 2013). Detailed descriptions of the available experimental data sets and references to computer programs used can be found on the DDEP web site ⟨http://www.nucleide.org/DDEP_WG/DDEPdata.htm⟩ in the section "Comments" for the respective nuclides. We give here below (only as an example illustrating the current DDEP half-life evaluation technology) a description of the evaluation of the ^{57}Co half-life.

Table 2 shows the 11 experimental values of the ^{57}Co half-life