Life Sciences in Space Research 3 (2014) 90–94

Contents lists available at ScienceDirect

Life Sciences in Space Research

www.elsevier.com/locate/lssr

Opinion/Position paper

# Space radiation accelerator experiments – The role of neutrons and light ions

John W. Norbury *, Tony C. Slaba

*NASA Langley Research Center, Hampton, VA 23681, USA*

ARTICLE INFO

*Article history:*
Received 4 September 2014
Received in revised form 18 September 2014
Accepted 29 September 2014

*Keywords:*
Space radiation
Neutrons
Light ions

ABSTRACT

The importance of neutrons and light ions is considered when astronauts spend considerable time in thickly shielded regions of a spacecraft. This may be relevant for space missions both in and beyond low Earth orbit (LEO). In addition to heavy ion experiments at accelerators, it is suggested that an increased emphasis on experiments with lighter ions may be useful in reducing biological uncertainties.

Published by Elsevier Ltd on behalf of The Committee on Space Research (COSPAR).

The detrimental effect of space radiation is a major obstacle that needs to be overcome for missions beyond low Earth orbit (LEO), such as a human mission to Mars (Durante, 2014). Of the various radiation environments in space, it is the galactic cosmic rays (GCR) that are the most problematic, not only because they are very difficult to shield against, but also because their biological effects are very uncertain. In order to reduce these uncertainties, a program of ground-based accelerator experiments has been underway at various facilities around the world (Durante et al., 2007; Sihver, 2008), such as the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) and the Facility for Antiproton and Ion Research (FAIR) at Gesellschaft für Schwerionenforschung (GSI). The nuclei from hydrogen to nickel and the energies from 100 MeV/n to 50 GeV/n are the most important radiation components in the GCR spectrum (Sihver, 2008; Slaba and Blattnig, 2014), and ground-based accelerators are designed to accelerate these GCR nuclei at the relevant energies. In addition to accelerator based biology experiments, there are also investigations devoted to the physics and transport mechanisms of GCR nuclei passing through various shielding materials.

The broad range of radiobiology experiments covering various particle types and energies have furthered our basic understanding of mechanisms through which radiation induces cancer and other tissue effects (Durante, 2014). A question is whether the research has matured to a point where one can take the knowledge gained and focus future studies on the particles and energies that are perhaps more relevant to deep space missions beyond LEO.

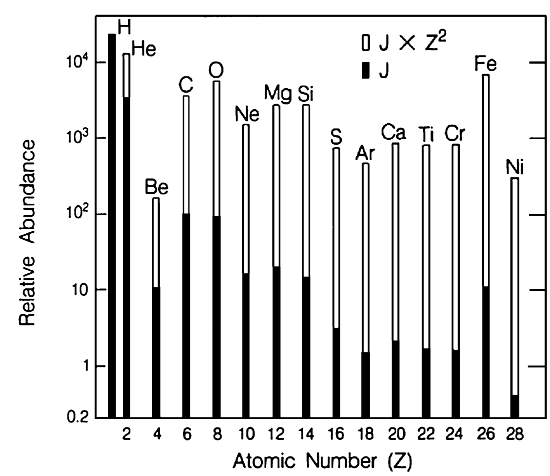


**Fig. 1.** Abundance (fluence) of galactic cosmic rays in free space (black bars). Open bars represent abundance multiplied by nuclear charge (Z) squared, which gives an estimate of the relative contribution to dose.
Reprinted from Wefel (1979) in the Public Domain.

There have been many space radiobiology experiments performed with heavy ions, especially iron (Fe) at 1 GeV/n at high dose rates (Maalouf et al., 2011; NCRP, 2006; Sihver, 2008). Herein, heavy ions are defined to be isotopes heavier than helium (He) and light ions are defined to be isotopes of hydrogen (H) and He only. Fig. 1 shows the abundance (fluence) of prominent GCR nuclei. Multiplying the abundance by charge ($Z$) squared gives an estimate of the relative contribution to dose, because linear

* Corresponding author.
*E-mail address:* john.w.norbury@nasa.gov (J.W. Norbury).

http://dx.doi.org/10.1016/j.lssr.2014.09.006
2214-5524/Published by Elsevier Ltd on behalf of The Committee on Space Research (COSPAR).

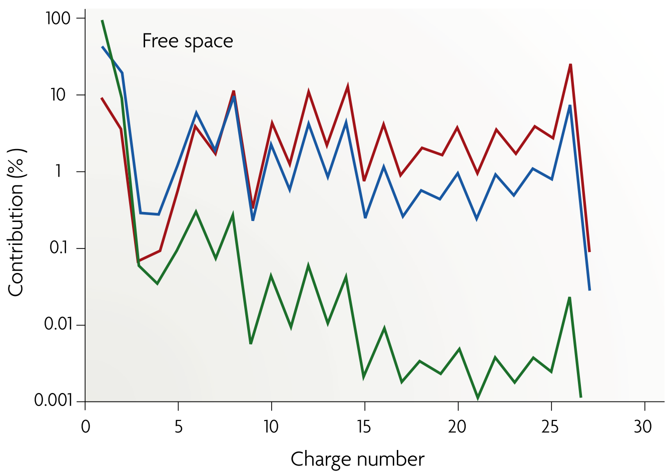


**Fig. 2.** Abundance (fluence) (green curve) of galactic cosmic rays in free space. Dose (blue curve) and dose equivalent (red curve) are calculated behind 5 g/cm$^2$ of aluminum shielding in free space averaged over a year during solar minimum. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Reprinted from Durante and Cucinotta (2008) with permission from the publisher. A similar figure appears in Cucinotta et al. (2003) and Durante and Cucinotta (2011).

energy transfer (LET) scales with $Z^2$. It can be seen that even though heavy ions have a relatively small abundance compared to light ions, the heavy ions nevertheless make large contributions to dose, especially when all heavy ion contributions are summed together.

Fig. 2 gives a similar result, again showing abundance (fluence) and dose, but also dose equivalent. Note that the label "free space" in the figure indicates that the results were computed within a 5 g/cm$^2$ spherical aluminum shield in free space (not in LEO or on a planetary surface). The combined results for heavy ions again show that heavy ions make a large contribution to dose and dose equivalent. Similarly Fig. 3, which shows contributions to dose equivalent and other biological end points, gives large contributions from heavy ions.

However, it should be emphasized that Fig. 1 is for free space with no shielding and Figs. 2 and 3 show results for a shield thickness of 5 g/cm$^2$. It is expected that vehicle shielding thicknesses for a long duration, deep space mission will be larger. Townsend et al. (2006) state that typical spacecraft shielding thickness is about 10 g/cm$^2$. Shielding on Apollo averaged about 7–8 g/cm$^2$ and the space shuttle averaged about 10 g/cm$^2$ (Cucinotta, 2005). The Martian atmosphere will provide significant shielding during a stay on the surface. The average thickness of both the International Space Station (ISS) and the vertical depth of the Martian atmosphere has been stated to be about 20 g/cm$^2$ (Durante and Cucinotta, 2011; Cucinotta et al., 2013). Further, a Martian habitat would provide at least an additional 10 g/cm$^2$ (Cucinotta et al., 2013). Most importantly, the average thickness of the Orion spacecraft has been stated to be about 20 g/cm$^2$ (Cucinotta et al., 2013). The human body has an average thickness of about 30 g/cm$^2$ (Slaba et al., 2010). (Note that thickness estimates vary and it is unclear whether some thickness numbers include everything in the vehicle, such as cargo, water, other humans etc. ISS may well be thicker than 20 g/cm$^2$ and Orion may have locations that are not nearly as thick. Also, some sources quote median and not average.)

What are the contributions from heavy ions behind thicker shields? The general result has been known for some time, at least for simple geometries. Fig. 4 shows dose equivalent results for aluminum slab shielding as a function of shield thickness. It can be seen, in agreement with the previous figures, that heavy ions dominate the contribution to dose equivalent for thin shielding. However, as the shielding thickness increases to 20 g/cm$^2$ and beyond, the majority of the contribution is from neutrons and light ions. Similarly Fig. 5, again shows that light ions dominate dose equivalent for thick polyethylene slab shielding.

Of course, real spacecraft contain both thinly shielded areas and thickly shielded areas, and therefore, one cannot make general conclusions about astronaut exposures by simple extrapolations from slab geometries. One must consider realistic spacecraft vehicles. Such a study was done recently by Walker, Townsend and

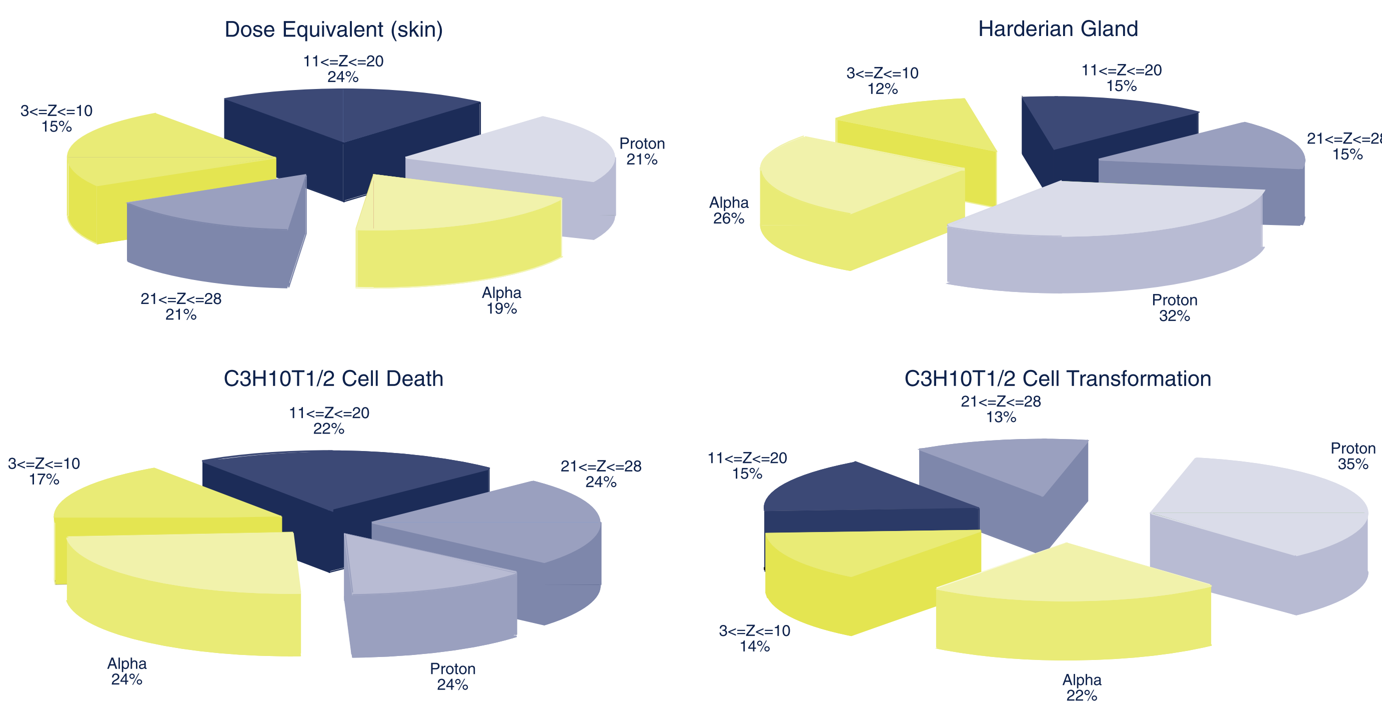


**Fig. 3.** Contributions from various nuclei to dose equivalent and various biological end points behind 5 g/cm$^2$ of aluminum shielding in free space. Reprinted from NASA (1998) in the Public Domain. A similar figure appears in Durante and Cucinotta (2011).