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Nuclear physics and space radiation

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Abstract. Nuclear fragmentation reactions induced by alpha particle projectiles are an important component of the space radiation problem. Inclusive isotopic spectral distributions and double differential cross sections are used as input to the Boltzmann transport equation, which is often solved in many space radiation applications. For alpha particle projectiles, it is found that most of the available experimental data are below the pion threshold. This is a significant validation gap because the important energy range for galactic cosmic rays extends up to 10 GeV/n and above.

1. Introduction

Ernest Rutherford discovered the atomic nucleus [1] one hundred years ago by scattering alpha particles from gold foil and observing large angle deflections, which are indicative of a tiny atomic core. The alpha particles had kinetic energies of only a few MeV. Of the nuclear component of the galactic cosmic ray (GCR) spectrum, approximately 12% of the particles are alphas. The spectrum extends up to 10 GeV/n and beyond. Due to their large penetration depth and production from heavier nuclear reactions, alpha particles constitute an important piece of the space radiation problem, in which one tries to protect humans and electronics from the harmful effects of high energy particles found in the GCR environment. It is common to use fast deterministic transport codes for space radiation problems, which entail solving the Boltzmann transport equation (BTE).

The BTE uses nuclear fragmentation cross sections as input, and therefore, one requires accurate cross section models which need to be validated against experimental measurements. The present work will review the available data for alpha projectiles that can be used to directly validate the cross sections which are input to the BTE. It will be found that there are significant gaps in the available data.

2. Transport

In the continuous slowing down approximation, the time independent 3-dimensional BTE is [2]

$$\left[\mathbf{\Omega}\cdot\mathbf{\nabla} - \frac{\partial}{\partial E}S_j(E) + \tilde{\sigma}_j(E)\right]\phi_j(\mathbf{r},\mathbf{\Omega},E) = \sum_k \int dE' \int d\mathbf{\Omega}'\ \tilde{\sigma}_{jk}(\mathbf{\Omega},\mathbf{\Omega}',E,E')\phi_k(\mathbf{r},\mathbf{\Omega}',E') \quad (1)$$

where $\phi_j(\mathbf{r},\mathbf{\Omega},E)$ is the flux of isotope j at position $\mathbf{r}$ moving in direction $\mathbf{\Omega}$ with energy E, $\tilde{\sigma}_j(E)$ is the isotopic total absorption cross section of isotope j with kinetic energy E, $\tilde{\sigma}_{jk}(\mathbf{\Omega},\mathbf{\Omega}',E,E')$ is the inclusive isotopic double differential cross section for producing isotope j moving in direction $\mathbf{\Omega}$ with kinetic energy E from isotope k moving in direction $\mathbf{\Omega}'$ with energy

E', and $S_j(E)$ is the stopping power of isotope j. Note, the cross sections are macroscopic and are related to the usual microscopic cross sections via the relation $\tilde{\sigma} = \tilde{\rho}\sigma$, where the number of nuclei per unit gram is $\tilde{\rho} = N_A/A$, with N_A being Avagadro's number and A is the nuclear mass number. The double differential cross section is often written as

$$\sigma_{jk}(\mathbf{\Omega}, \mathbf{\Omega}', E, E') \equiv \frac{d^2\sigma}{dE_j d\mathbf{\Omega}_j} \tag{2}$$

with $\mathbf{\Omega}_j \equiv \mathbf{\Omega}$ and $E_j \equiv E$.

In the straight ahead approximation, the BTE becomes 1-dimensional [1 - 9]

$$\left[\frac{\partial}{\partial x} - \frac{\partial}{\partial E} S_j(E) + \tilde{\sigma}_j(E)\right] \phi_j(x, E) = \sum_k \int dE' \ \tilde{\sigma}_{jk}(E, E')\phi_k(x, E') \tag{3}$$

where $\phi_j(x, E)$ is the flux of isotope j at position x with kinetic energy E, $\tilde{\sigma}_{jk}(E, E')$ is the inclusive isotopic energy single differential cross section for producing isotope j with kinetic energy E from isotope k with energy E'. The differential cross section is often written as

$$\sigma_{jk}(E, E') \equiv \frac{d\sigma}{dE_j} \tag{4}$$

with $E_j \equiv E$.

3. Experimental data

Many nuclear models are capable of predicting a variety of different cross section types, such as charge changing, elemental and isotopic cross sections or total, single differential and double differential cross sections. A nuclear fragmentation database has been constructed [11], which contains information on all nuclear fragmentation experiments relevant to space radiation, with the exception of neutrons. Comparisons with corresponding experimental data are used to validate models. However, as shown above, the cross sections actually appearing in the Boltzmann equations are total isotopic absorption cross sections and isotopic spectral distributions and isotopic double differential cross sections. The question being addressed is whether there is available experimental data for those cross sections actually being used in the BTE. In deference to Rutherford, attention is confined to alpha particle projectiles only. More general reactions have been considered in reference [11].

Figure 1 shows the available experimental spectral distribution data for H and He isotope production. The symbols represent the availability of measured cross section data. There are no other data available for energies above the pion threshold of 280 MeV/n. There are no data available for a H target, which is an important space radiation protection material. Other target materials are relatively sparse.

Figure 2 shows the available experimental double differential cross section data for H and He isotope production. There are no other data available for energies above 3 GeV/n. The data below the pion threshold are well represented, but there are very few data above this energy.

4. Conclusions

Experimental measurements of nuclear fragmentation reactions are used to validate theoretical models, which are input to the Boltzmann transport equation commonly solved in space radiation applications. A database has been constructed which contains information on all nuclear fragmentation reactions relevant to space radiation. Neutrons are not yet included. For alpha particle projectiles, it is found that most of the available spectral and double differential cross section data are below the pion threshold. This situation significantly hampers validation of nuclear models used for space radiation studies, which are required to be valid up to energies of tens of GeV/n.

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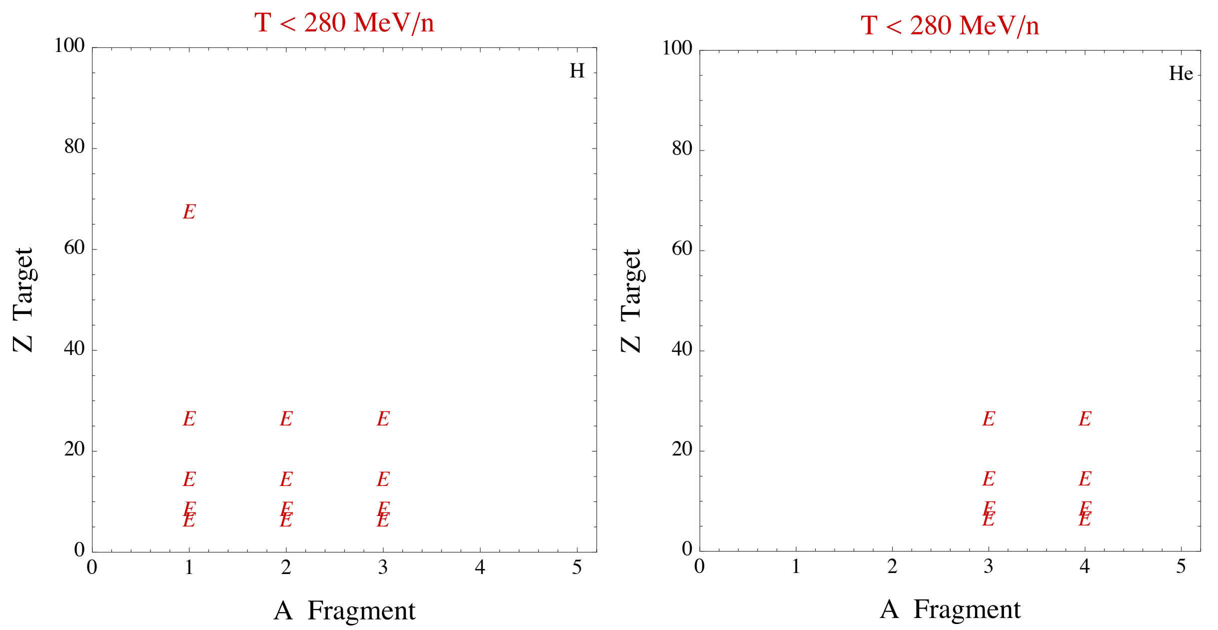

Figure 1. Alpha projectile isotopic spectral distributions ($\frac{d\sigma}{dE}$) for H (left panel) and He (right panel) fragment production. There are no data at other energies or for heavier mass fragments.

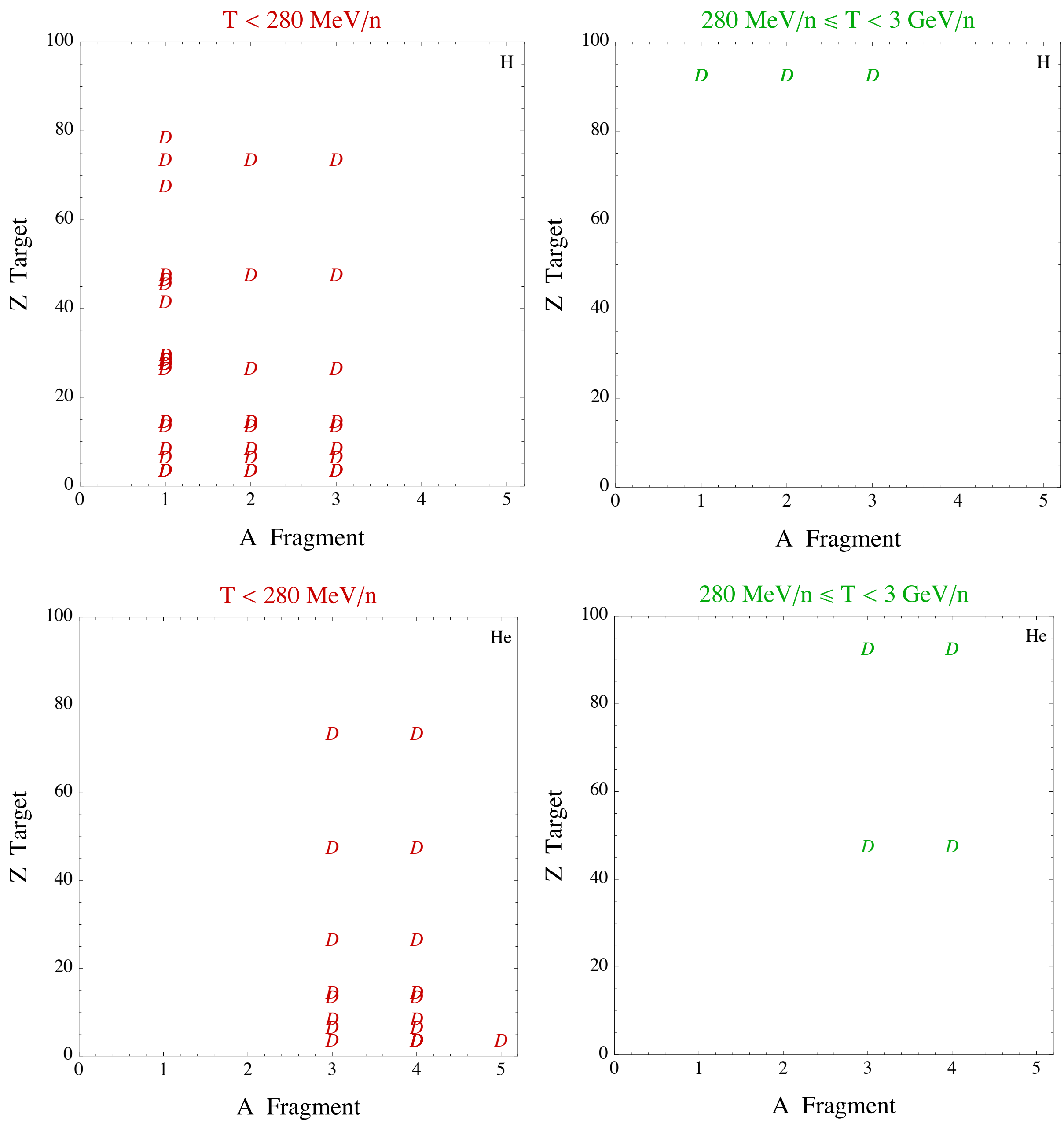

Figure 2. Alpha projectile isotopic double differential cross sections ($\frac{d^2\sigma}{dEd\Omega}$) for H (top panels) and He (bottom panels) fragment production. There are no data at other energies or for heavier mass fragments.