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Light ion and multiple nucleon removal due to electromagnetic dissociation

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Light ion (H and He isotopes) and neutron production in galactic cosmic ray interactions are important for space radiation analyses. They occur via strong or electromagnetic dissociation (EMD) interactions. A parameterization for single nucleon, multiple nucleon and light ion production in EMD is developed in this paper. It supersedes the previous work in the following ways. Firstly, the calculations are compared to a more extensive set of experimental data. Secondly, EMD calculations for alpha particle production are in better agreement with experiment. Thirdly, a parameterization of multiple nucleon removal is developed and compared to data. Overall, the present work includes more reactions and compares better to experimental data than previous work.

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1. Introduction

The harmful effects of space radiation are a serious concern for long duration spaceflight [1]. Galactic cosmic ray interactions are an important piece of the space radiation problem and proceed through relativistic nucleus–nucleus collisions, where the two most important interactions are strong and electromagnetic (EM). When the colliding nuclei emit nuclear fragments as a result of EM interactions, the process is called electromagnetic dissociation (EMD). It has been shown [2] that EMD contributes significantly to nuclear reactions of interest in space radiation. The NUClear FRaGmentation model called NUCFRG2 [3,4] is an example of a model that includes both strong and electromagnetic interactions between the colliding nuclei. Many different types of fragments are produced. Light ion fragments (isotopes of H and He) are especially important due to their abundance and ability to penetrate large depths. They are also the most dominant product in EMD reactions. Whereas the NUCFRG2 [3,4] code only includes single nucleon production via EMD, the present work provides calculations for multiple nucleon production and other light ions.

There have been several previous studies of EMD reactions as they apply to space radiation [3,5,6]. The first work [6] developed a concise parameterization for EMD reactions, but only compared to a limited experimental data set that was available at that time. Since then, there have been many more experiments. In the present work, the calculated EMD cross-sections will be compared to the full set of data now available. The second work [3] implemented EMD calculations within the nuclear fragmentation model NUCFRG2. However, the EMD formalism was only capable of describing single nucleon removal. Alpha particles and multiple nucleon emission were not included in the EMD calculations. This defect was cured in the third work [5], which included EMD processes in a new nuclear fragmentation model called NUCFRG3. This model also introduced a coalescence model for strong interaction production of light ions. The EMD calculations of NUCFRG2 used a simple parameterization of photonuclear cross-sections used as input into EMD calculations, whereas the EMD calculations of NUCFRG3 used the more sophisticated Weisskopf–Ewing formalism [7] to calculate the input photonuclear cross-sections. Despite providing a consistent theoretical formalism with which to handle alpha particles in the EMD portion of NUCFRG3, the results for alpha production did not agree well with experimental data and some of the single nucleon results for O and C projectiles were actually worse in NUCFRG3 compared to NUCFRG2. In addition, NUCFRG3 did not include multiple nucleon emission via EMD.

The present work represents a continuation of the effort to obtain calculated EMD cross-sections for alpha particles and other light ions and multiple nucleons. The NUCFRG2 calculations used a sum rule approximation [3], which includes an integral over all virtual photon energies and therefore does not include threshold effects. This is the reason that alpha particles and multiple nucleons could not be included because of their very different threshold energies. The sum rule approximation is removed in the present work, and the virtual photon spectrum is integrated from the particular reaction threshold of interest. However, compared to the Weisskopf–Ewing formalism, which uses energy dependent branching ratios, the present work will employ the simpler energy independent branching ratios. Nevertheless, it will be found that the present EMD parameterizations agree with experiment better than the EMD model in NUCFRG3. Finally, note that many of the equations in this paper have appeared in previous works. They are repeated (and referenced) here for the sake of

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completeness, so that the reader can more easily understand how the present calculations are done.

2. Electric dipole

In the electric dipole ($E1$) approximation, the total nucleus–nucleus electromagnetic dissociation (EMD) cross-section is given by an integral [6,8] over virtual photon energies E_γ

$$\sigma_{E1}^{\mathrm{EMD}} = \int dE_\gamma \, N_{E1}(E_\gamma)\sigma_{E1}(E_\gamma) \tag{1}$$

where $N(E_\gamma)$ is the virtual photon spectrum and $\sigma_{E1}(E_\gamma)$ is the photonuclear total cross-section. Photons are assumed to originate from the target nucleus exciting photonuclear reactions in the projectile. This process can be called projectile excitation. In Eq. (1), $N(E_\gamma)$ is the number of photons N with an energy E_γ provided by the target and $\sigma(E_\gamma)$ is the projectile photonuclear cross-section. The description can be reversed with the projectile providing photons which excite the target, to calculate cross-sections for reactions involving target excitation.

2.1. Virtual photon spectrum

The equations in this subsection come from Refs. [6,8–10]. As a function of impact parameter b, the Weiszacker–Williams electric dipole virtual photon spectrum is given by [9]

$$N_{E1}(E_\gamma,b) = \frac{1}{(\hbar c)^2}\frac{Z_T^2 \alpha E_\gamma}{\pi^2\gamma^2\beta^4}\left(K_1^2 + \frac{1}{\gamma^2}K_0^2\right) \tag{2}$$

with units of $\mathrm{fm}^{-2}\,\mathrm{MeV}^{-1}$. Here, Z_T is the number of protons in the target nucleus, β is the velocity of the target in units of c (speed of light), $\gamma = (1-\beta^2)^{-1/2}$ and α is the electromagnetic fine structure constant [11]. In Eq. (2), the terms $K_0 \equiv K_0(y)$ and $K_1 \equiv K_1(y)$ are modified Bessel functions of the second kind which are functions of the dimensionless variable y, defined as [9]

$$y \equiv \frac{E_\gamma b}{\gamma\beta\hbar c}. \tag{3}$$

The first order reaction probability is given by [9]

$$\Phi(b) = \int N_{E1}(E_\gamma,b)\sigma_{E1}(E_\gamma)\, dE_\gamma. \tag{4}$$

The photonuclear cross-section $\sigma_{E1}(E_\gamma)$ has units of mb. Note that the units of $N_{E1}(E_\gamma,b)$ must be converted to $\mathrm{mb}^{-1}\,\mathrm{MeV}^{-1}$, so that $\Phi(b)$ is dimensionless. This is accomplished by dividing $N_{E1}(E_\gamma,b)$ in Eq. (2) by 10, since $\mathrm{fm}^2 = 10$ mb.

When integrated over impact parameter, one obtains the Weiszacker–Williams electric dipole virtual photon spectrum independent of impact parameter [9]

$$N_{E1}(E_\gamma) = 2\pi\int_{b_{\min}}^{\infty} b\, db N_{E1}(E_\gamma,b) \tag{5}$$

$$= \frac{2Z_T^2\alpha}{\pi E_\gamma\beta^2}[xK_0K_1 - \beta^2x^2(K_1^2-K_0^2)/2] \tag{6}$$

which has units of MeV^{-1}. The parameter x is defined by [9]

$$x \equiv \frac{E_\gamma b_{\min}}{\gamma\beta\hbar c} \tag{7}$$

which is dimensionless. The quantity $b_{\min}$ is the minimum impact parameter which is approximately equal to the sum of the nuclear radii. $K_0 \equiv K_0(x)$ and $K_1 \equiv K_1(x)$ are modified Bessel functions of the second kind which are functions of x. Eqs. (4)–(6) show that Eq. (1) can be alternatively written as [10]

$$\sigma_{E1}^{\mathrm{EMD}} = 2\pi\int_{b_{\min}}^{\infty} b\, db\Phi(b). \tag{8}$$

2.1.1. Impact parameter

The minimum impact parameter, which takes into account Rutherford bending of the trajectory, is expressed as [12]

$$b_{\min} = b_c + \frac{\pi a_0}{2\gamma} \tag{9}$$

where the Rutherford bending parameter is given by [12]

$$a_0 = \frac{Z_\mathrm{P}Z_\mathrm{T}e^2}{m_0 v^2} = \frac{Z_\mathrm{P}Z_\mathrm{T}\alpha\hbar c}{(m_0c^2)\beta^2} \tag{10}$$

where $Z_\mathrm{P}e$ and $Z_\mathrm{T}e$ are the projectile and target charge. The reduced mass of the projectile-target system is given by $m_0 = A_\mathrm{P}A_\mathrm{T}/\,(A_\mathrm{P}+A_\mathrm{T})m_n$, where m_n is the nucleon mass. Also, v is the speed of the projectile in the lab frame (same as target frame). The critical impact parameter is [12]

$$b_c = 1.34\ \mathrm{fm}[A_\mathrm{P}^{1/3} + A_\mathrm{T}^{1/3} - 0.75(A_\mathrm{P}^{-1/3} + A_\mathrm{T}^{-1/3})] \tag{11}$$

with A_P and A_T being the nucleon number of the projectile and target.

Note that in the codes NUCFRG2 [3,4] and NUCFRG3 [5], an adjustable parameter x_d=0.25 was introduced so that Eq. (9) was given by $b_{\min} = (1+x_d)b_c + \pi a_0/2\gamma$. This adjustable parameter is absent in the present work.

2.2. Photonuclear absorption cross-section

The equations in this subsection come from Refs. [6,12]. The photonuclear absorption cross-section is parameterized as

$$\sigma_{E1}(E_\gamma) = \frac{\sigma_m}{1 + [(E_\gamma^2 - E_{\mathrm{GDR}}^2)^2/E_\gamma^2\Gamma^2]} \tag{12}$$

where E_{GDR} is the peak energy of the giant dipole resonance (GDR) cross-section, and

$$\sigma_m \equiv \frac{\sigma_{\mathrm{TRK}}}{\pi\Gamma/2} \tag{13}$$

with the Thomas–Reiche–Kuhn $E1$ sum rule cross-section given by

$$\sigma_{\mathrm{TRK}} \equiv \sigma_{E1}^{\mathrm{sum}} \equiv \int dE_\gamma\ \sigma_{E1}(E_\gamma) = \frac{60NZ}{A}\,\mathrm{MeV\ mb} \tag{14}$$

where N, Z, A are the neutron, proton and mass numbers of the nucleus involved in photonuclear excitation. The GDR width Γ is parameterized as

$$\Gamma = \begin{cases} 10\ \mathrm{MeV} & \text{for } A < 50 \\ 4.5\ \mathrm{MeV} & \text{for } A \geq 50. \end{cases} \tag{15}$$

The GDR energy, given in Eq. (12), is expressed as

$$E_{\mathrm{GDR}} = \hbar c\left[\frac{m^*c^2R_0^2}{8J}\left(1 + u - \frac{1+\epsilon+3u}{1+\epsilon+u}\epsilon\right)\right]^{-1/2} \tag{16}$$

with

$$u \equiv \frac{3J}{Q'}A^{-1/3} \tag{17}$$

and

$$R_0 = r_0A^{1/3}. \tag{18}$$

The parameters are defined as $\epsilon = 0.0768$, $Q' = 17$ MeV, $J =$ 36.8 MeV, $r_0 = 1.18$ fm, and $m^* = 0.7\,m_n$, where $m_n = 938.919$ MeV/c^2 is the nucleon mass, taken as the average of the proton and neutron mass [11].