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Vital role of nuclear data in space missions

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Abstract. NASA has a new vision for space exploration in the 21st Century encompassing a broad range of human and robotic missions including missions to Moon, Mars and beyond. Exposure from the hazards of severe space radiation in deep space long duration missions is a critical design driver. Thus, protection from the hazards of severe space radiation is of paramount importance for the new vision. Accurate risk assessments critically depend on the accuracy of the input information about the interaction of ions with materials, electronics and tissues. A huge amount of essential experimental information of nuclear data for all the ions in space, across the periodic table, for a wide range of energies of several (up to a trillion) orders of magnitude are needed for the radiation protection engineering for space missions that is simply not available (due to the high costs) and probably never will be. One is required to know how every element (and all isotopes of each element) in the periodic table interacts and fragments on every other element in the same table as a function of kinetic energy ranging over many decades. In addition, the accuracy of the input information and database, in general and nuclear data in particular, is very critical and of paramount importance for space exposure assessments particularly in view the agency's vision for deep space exploration. As a result, very accurate and reliable analytical models/tools are needed to describe nuclear interactions that are not available so that radiation risks can be assessed and adequate shielding can be designed. State-of-the-art nuclear cross sections models have been developed at the NASA Langley Research Center. An overview of the vital role and importance of nuclear data for space missions with a couple of examples are discussed.

1 Introduction

Accurate nuclear interaction databases are needed for describing the transport of space radiation in matter including spacecraft structures, atmospheres, and tissues. Transport models support the identification and development of new material concepts for human and electronic part protection. The success of the Human Exploration and Development of Space program in NASA critically depends on the minimizing the exposure to astronauts from galactic cosmic rays, solar particle events in deep space for which there is, as yet, little human experience. The usual method for reduction of exposure is the design of shield for specific missions. The types and energy distributions of particles transmitted through a shield material require the solution to a transport description of the process with appropriate boundary conditions. The relevant transport equations are the linear Boltzmann equations derived on the basis of conservation principles for the flux density $\phi_j\,(\mathbf{x}, \mathbf{\Omega}, \mathrm{E})$ of type j particles at $\mathbf{x}$ of energy E moving in direction $\mathbf{\Omega}$ as

$$\mathbf{\Omega} \cdot \nabla\phi_j(\mathbf{x}, \mathbf{\Omega}, \mathrm{E}) = \sum \int \sigma_{jk}(\mathbf{\Omega}, \mathbf{\Omega}', \mathrm{E}, \mathrm{E}')\phi_k(\mathbf{x}, \mathbf{\Omega}', \mathrm{E}')\, d\mathbf{\Omega}' d\mathrm{E}' - \sigma_j(\mathrm{E})\phi_j(\mathbf{x}, \mathbf{\Omega}, \mathrm{E}) \tag{1}$$

where σ_j (E) and $\sigma_{jk}(\mathbf{\Omega}, \mathbf{\Omega}', \mathrm{E}, \mathrm{E}')$ are the media macroscopic total and fragmentation cross sections. The σ_{jk} $(\mathbf{\Omega}, \mathbf{\Omega}', \mathrm{E}, \mathrm{E}')$ represents all those processes by which type k particles moving in direction $\mathbf{\Omega}'$ with energy E′ produce a type j particle in direction $\mathbf{\Omega}$ with energy E. Note that there may be several reactions that produce a particular product, and the appropriate cross sections for equation (1) are the inclusive ones. Accuracy of the input cross sections is of prime concern to the projects. The design and thickness of shield sensitively depends on this input information significantly impacting on the payload and the feasibility of space missions.

2 Cross section models

Nuclear interaction cross section databases are required for the transport of cosmic rays with energies below 10 A MeV to energies above tens of A GeV, including a large number of projectile and target material combinations. The types of cross sections required for transport involve total yields and secondary energy spectra for one-dimensional transport and double differential cross sections in angle and energy for three-dimensional transport. Neutron and proton cross sections have been studied at some length in the past. Nuclear-reaction modeling is required, especially for both light and heavy ion projectiles, to understand the basic physical processes, and to extrapolate limited experimental data between projectile energies and projectile-target combinations. Our effort in developing nuclear cross sections models in NASA have largely focused in two directions (i) Semi-empirical/phenomenological and (ii) Microscopic. The emphasis in our work is on the accuracy of the results where experimental results are available and predicting reliable results where data are not available. The details of some models, comparisons with experiments and other challenging nuclear physics issues related to space missions are discussed.

2.1 Semi-empirical/phenomenological models

The semi-empirical/phenomenological model for fragmentation NUCFRG2 [1] and for absorption ABSXSEC [2],

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have modeled the essential physics. These models are coupled to the transport codes and, therefore, are meant to be very fast and accurate and give excellent results for the fragmentation and absorption cross sections.

2.1.1 Absorption cross sections model

The ABSXSEC model calculates the absorption cross sections for the collision of light, medium, heavy, charged and/or uncharged ions. The model gives excellent results for a wide rage of energies from a few A MeV to a few A GeV. ABSXSEC has become state-of-the art in the literature and is widely used here in the USA and else where around the world. The model incorporates essentials aspects of the physics of the collision systems like Coulomb interaction, Pauli blocking, transparency, asymmetry and isotopic effects. Figure 1 shows the results of the model for a few collision systems. It is gratifying to note the model has excellent agreement up to six orders of magnitude in energy (e.g., p + α).

2.2 Microscopic cross sections models

The microscopic model for fragmentation QMSFRG [3] and the general purpose OPTICAL MODEL [4] are based on multiple scattering theory. For high-energy reactions, the eikonal approximation, which assumes that the scattering is peaked at the forward angles, simplifies the solution of multiple scattering series. OPTICAL MODEL, in addition, uses nucleon-nucleon (NN) cross sections and the ratio of the real to imaginary part of the two-body scattering amplitudes in the medium and calculates absorption, total and fragmentation cross sections thus providing a comprehensive picture of the input information for the radiation protection and shielding projects of NASA space missions. QMSFRG: incorporates statistical methods for the analysis of continuous excitation energy distribution of the pre-fragments. This approach allows nuclear structure and clustering effects to be considered. As a result, this model explains features like odd-even effects of the fragmentation cross sections. These models have been very successful in predicting experimental results.

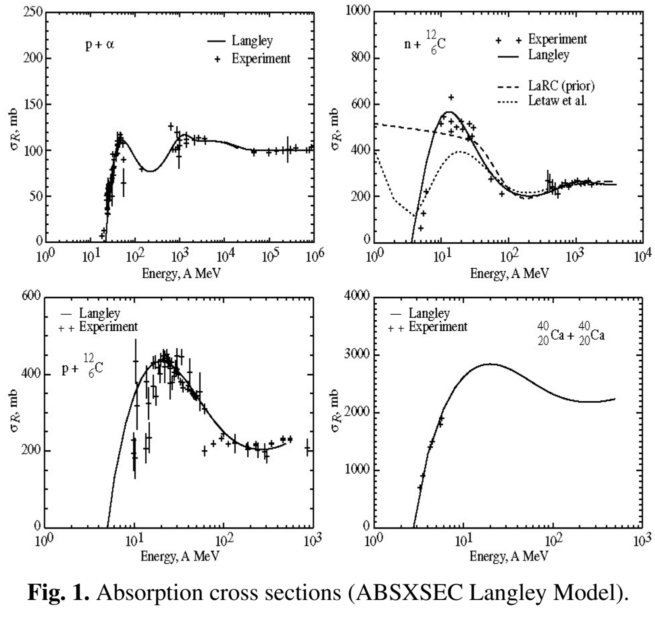


Fig. 1. Absorption cross sections (ABSXSEC Langley Model).

2.2.1 Optical model approach

The model is based on coupled-channel multiple scattering approach (see ref. [4] and refs. there in for details). In this the basic quantity is the matrix for elastic scattering amplitude,

$$\mathrm{f}(\mathbf{q}) = -\frac{\mathrm{ik}}{2\pi}\int \mathrm{d}^2\mathbf{b}\,\exp(-\mathrm{i}\mathbf{q}\cdot\mathbf{b})\{\exp[i\chi(\mathbf{b})]-1\} \qquad (2)$$

where f and χ represent matrices, k is the projectile momentum relative to the center of mass, b is the projectile impact parameter vector, q is the momentum transfer, and χ(b) is the eikonal phase matrix. The total cross section can be easily obtained from the elastic scattering amplitude by using the optical theorem

$$\sigma_{\mathrm{tot}} = 4\pi\int_0^{\infty}\mathrm{d}b\,b\left\{1-\mathrm{e}^{-\mathrm{Im}(\chi)}\cos(\mathrm{Re}(\chi))\right\}, \qquad (3)$$

and the absorption cross sections (σ_{abs}) is given by

$$\sigma_{\mathrm{abs}} = 2\pi\int_0^{\infty}\mathrm{d}b\,b\left\{1-\mathrm{e}^{-2\mathrm{Im}(\chi)}\right\}. \qquad (4)$$

Having calculated the total and absorption cross sections, for many nuclei, elastic cross section is easily obtained by the difference of these quantities,

$$\sigma_{\mathrm{el}} = \sigma_{\mathrm{tot}} - \sigma_{\mathrm{abs}}. \qquad (5)$$

We developed a method of extracting nucleon-nucleon (N-N) cross sections in the medium directly from experiment. The in-medium N-N cross sections form the basic ingredients of several heavy-ion scattering approaches including the coupled-channel approach developed at the NASA Langley Research Center. We investigated the ratio of real to imaginary part of the two body scattering amplitude in the medium. These ratios are used in combination with the in-medium N-N cross sections to calculate total, absorption and elastic proton-nucleus cross sections. The agreement with the available experimental data has been found to be excellent for all these cross section. Figure 2 shows the examples of absorption and total cross sections for various systems.

3 Impact on space missions

To demonstrate the vital role of nuclear data on space missions, we consider a 30-day lunar mission for casual and career astronauts. We assume that casual astronauts make a single mission to Moon on the other hand career astronauts make a couple of missions a year for a period expanding ten years with a mixed crew of six in both the cases. The optimum volume of living space is taken as 114 m^3 and crew age set at the youngest female. It is assumed that the living space is a right circular

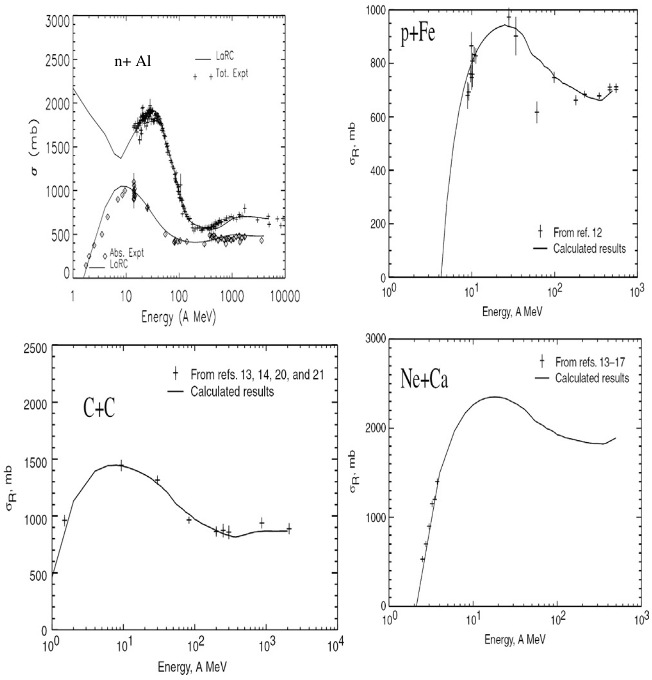


Fig. 2. Absorption and total cross sections (optical model).

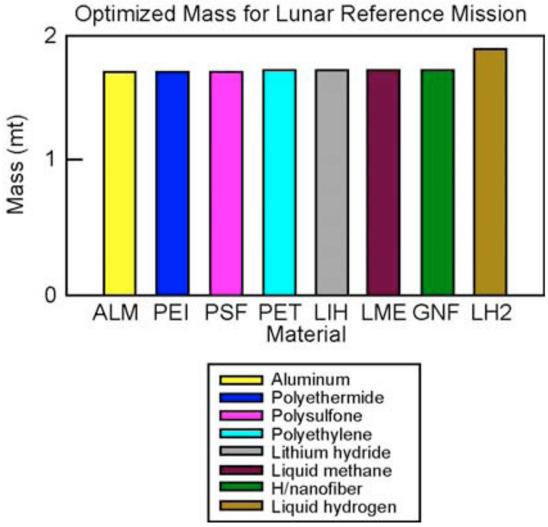


Fig. 3. Radiation shielding for casual astronauts (materials in figure from left to right are identified in the legend from top to bottom).

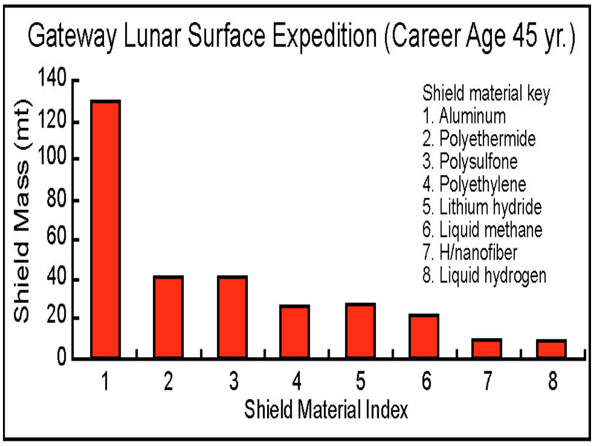
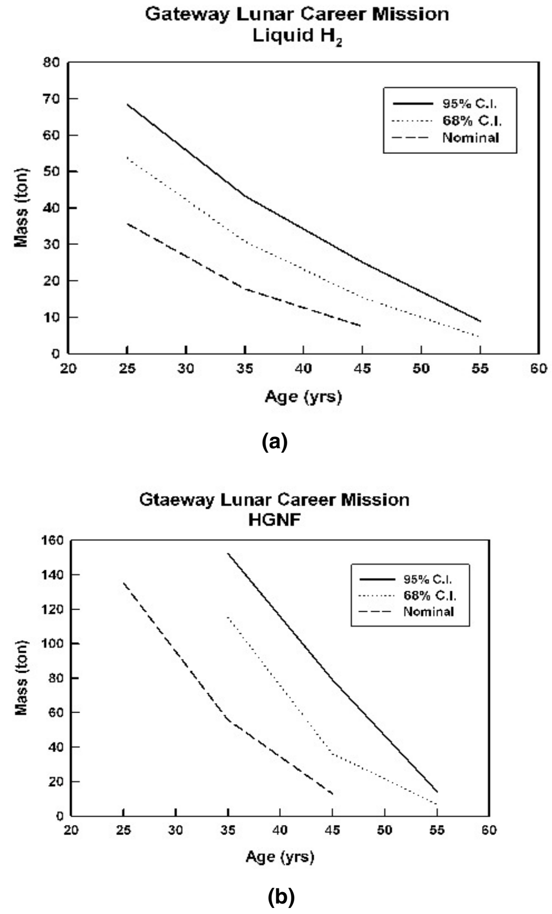


Fig. 4. Radiation shielding for career astronauts.



(a)

(b)

Fig. 5. The stochastic design space for a 30-day lunar mission for career astronauts: (a) liquid H2, (b) HGNF.

cylinder 2.2 m high. Shield optimization was investigated for a variety of materials: Aluminum, polyethermide, polysulfone, polyethylene, lithium hydride, liquid methane, hydrogenated nanofiber (HGNF), and liquid hydrogen. The reason for the choice of the materials is that there is increasing hydrogen content in the materials as we go down the list from aluminum to liquid hydrogen. We have established that hydrogen is a better space shielding material. As a result, the more the hydrogen content the better the material is expected to perform for space radiation shielding. Figure 3 shows optimized mass for single Lunar mission for casual astronauts. Notice that for a single moon mission, the choice of the material is not so important, but for long duration space missions as for career astronauts, figure 4, liquid hydrogen and HGNF out performs other materials. As a result, reliability analysis is discussed for these two materials. Although this is not the exact geometry and only the shield wall is represented we see a large impact of uncertainty on the design as shown in figure 5.

Recalling that HGNF is a factor of 4 to 6 more efficient at protecting the astronaut than aluminum, it is clear that few material options are available for future deep space mission explorations and other methods such as biological countermeasures will play a pivotal role. At the very minimum from an engineering design point of view, reliability based methods must be implemented to accurately portray the shielding component of risk mitigation in mission design.

4 Conclusions

We have discussed some of the state-of-the-art cross sections database at NASA and have demonstrated the role nuclear interaction plays in space missions. Database discussed here and in the cited references are available on request. The impact of the cross sections on space missions has been shown by the assessment of dose exposure on Moon surface behind a number of materials with increasing hydrogen contents known to be a better radiation shielding material. In addition we have examined an approach to introduce reliability based design methods into shield evaluation and optimization procedure as a means to assess and control the uncertainties in shield design. Applications to Lunar missions for short and long-term duration display a large impact on the design outcome and the choice of the materials. For short duration missions all the examined materials have similar performance. However, for career astronauts who are exposed to longer duration space radiation over the period of time the choice of material plays a very critical role. Computational procedures based on deterministic solution of the Boltzmann equation are well suited for such procedures allowing optimization processes to be implemented, evaluation of biologically important rare events, and rapid analysis of possible shield optimization outcomes resulting from the biological model uncertainty parameter space. Shield design studies based on nominal biological response models are highly questionable in their result and may lead to designs in which astronaut risk are much higher than anticipated on the basis of such models. Reliability based methods result in designs for which astronaut risk within the limitations of current knowledge is well controlled in the design process. The analysis provides enabling technology for protecting astronauts and missions for long duration and deep space missions. Current technology is adequate for a single lunar mission. For career astronauts, exposed to long duration space radiation revolutionary technology needs to be developed.

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