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Nuclear data for space exploration

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Understanding the harmful effects of galactic cosmic rays (GCRs) on space exploration requires a substantial amount of nuclear data. Specifically, the interaction of energetic GCR charged particles with spacecraft materials generates secondary radiations that, through energy deposition, can harm astronauts and electronic systems. By identifying the gaps in our knowledge of the relevant nuclear data—such as interaction cross sections—and identifying ways to fill those gaps—with measurements, compilations, evaluations, dissemination, reaction modeling, sensitivity studies, and uncertainty quantification—the safety and viability of space exploration can be improved. This work surveys the state of the art in this interdisciplinary field and identifies promising collaborative research topics that have significant potential to advance our understanding of the effects of the space radiation environment on space exploration.

KEYWORDS

space radiation, cosmic rays, nuclear data, heavy ions, nuclear reaction, cross section, spacecraft design, space electronics

1 Introduction

Nuclear data has a wide range of utilizations, both in basic research and in applied fields. Space exploration is one of the applications where nuclear data plays a critical role—primarily due to the harmful effects of the space radiation environment. While both the nuclear science and space communities have identified many of the relevant nuclear physics issues to enable safe space exploration, they have been working relatively independently to address them.

In recent years, a series of meetings—the Workshop on Applied Nuclear Data Activities (WANDA) (Bernstein et al., 2015; Romano et al., 2018; Bernstein et al., 2019; Romano et al., 2020; Kolos et al., 2022)—have brought together nuclear data producers, nuclear data users, basic and applied researchers, facility representatives, program managers, and funding agency officials, with the goals of identifying gaps in our nuclear data knowledge and setting prioritized goals to fill those gaps. At the WANDA 2022 meeting (Kolos and Pierson, 2022), sessions were held to enhance communication between these two communities, with the aim of identifying topics where collaborative efforts may be particularly impactful. This report is focused on topics relevant for the interactions of galactic cosmic rays with spacecraft materials, and the subsequent harmful effects on humans and electronics of the secondary radiations generated by those interactions.

The wide range of energies (up to ~TeV) and species ($Z \sim 1–28$) of GCRs (Badhwar and O'Neill, 1992) make it very challenging to determine all of their potential effects on spacecraft and astronauts. However, this wide variety of particle characteristics produces overlaps of space research with many areas of nuclear science, including spallation sources,

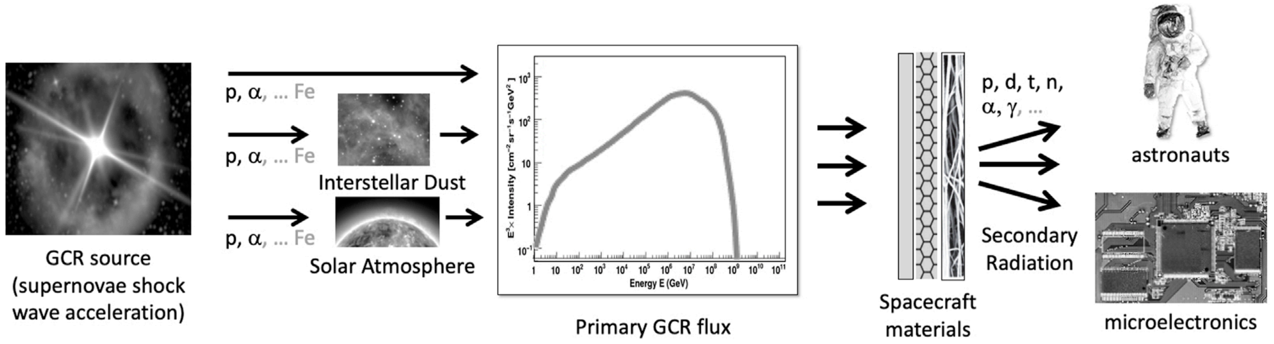

FIGURE 1
Primary and secondary galactic cosmic rays (GCR).

isotope production, ion beam analysis, fusion reactions, nucleosynthesis, fission reactors, and more. These overlaps can be exploited to better understand how to shield space missions most effectively from the effects of GCRs.

The flux and elemental composition of GCR "primaries," which are well characterized as functions of energy (Fu et al., 2021), serve as the foundation for studies of their interaction with matter. Our atmosphere provides a protective barrier against direct effects of GCR primaries on Earth-based systems (and humans). The showers of particles (e.g., pions, muons, neutrinos, electrons, gamma rays) generated via collisions of GCRs with nuclei (e.g., ^{14}N) in the atmosphere are overwhelmingly harmless, with only a small fraction reaching the Earth's surface (Mironova et al., 2015).

Above the atmosphere, however, the GCRs provide a serious impediment to the safety and viability of space exploration. Damage from GCR primaries can be serious, especially the 1% of primaries heavier than He, because the damage they inflict scales as Z^2. Additionally, GCR primaries interact with spacecraft materials (Finckenor and Bhat, 2018) (for example, aluminum, polyethylene, and composites) to generate a complex cascade of secondary radiation (light ions, neutrons, gamma rays) (Simonsen et al., 2020) which can further harm astronauts and disrupt or disable electronic systems (Figure 1). The shielding used to reduce the GCR flux also serves as a target that can increase the secondary flux. Because of the wide variety of possible shielding materials and thicknesses, modeling is essential to determine the sensitivity of the secondaries (both flux and composition) to different shielding configurations, as well as to determine the subsequent harmful impact of those secondaries on electronic systems and humans.

The relevant modeling efforts for space exploration include simulations of the transport of primaries through materials to determine the flux and composition of secondaries, the stopping of secondaries in electronic systems and tissue and the resulting damage from the deposited energy, and the overall design of spacecraft to optimize shielding configurations given all relevant constraints (e.g., weight, volume, dose limits).

These simulations require, as input, *nuclear data*—specifically, nuclear cross sections of GCR particles of energies up to hundreds of GeV/u interacting with H, C, O, Al, Si, and Fe targets that represent materials commonly found in spacecraft and in astronauts (Norbury et al., 2020). This is an area of specialization of the nuclear data community which requires efforts in a number of activities—namely, in experimental measurements, compilation, evaluation, databases, dissemination, reaction modeling, and uncertainty quantification. These activities are generally described as the "nuclear data pipeline" (see Schnabel et al., 2021; Kolos et al., 2022 and Figure 1 of Kolos et al., 2022), the sequential steps needed to determine and distribute recommended values of cross sections in formats needed for end-user applications, such as the space simulations mentioned above.

In the next section (Section 2), we will detail the current status and nuclear data gaps relevant for space exploration, in the areas of experiments, databases, dissemination, compilation, reaction models, radiation transport, electronics effects, human effects, spacecraft design, sensitivity studies, and uncertainty quantification. In Section 3, we describe a number of interdisciplinary research efforts that have the potential to significantly advance the state-of-the-art in space research, and thereby increase the safety and viability of the exploration of outer space. This is followed by a brief summary in Section 4.

2 Current status and nuclear data gaps

We detail the current the state-of-the-art and the relevant nuclear data gaps for experimental measurements, compilation, databases, dissemination, reaction models, sensitivity studies, and uncertainty quantification relevant for space science. We also detail a number of critical end-user applications including transport simulations, studies of effects on electronics, humans, and spacecraft design. We place an emphasis on areas of space research that can most benefit from cross-disciplinary collaborative research efforts.

2.1 Experimental facilities

In the US, there are five facilities that carry out nuclear experiments for space research: the Radiation Effects Facility at Texas A&M University (TAMU) (Texas A&M University, 2023); the Berkeley Accelerator Space Effects (BASE) facility at Lawrence Berkeley National Laboratory (LBNL) (University of California Berkeley, 2023); the NASA

Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) (Brookhaven National Laboratory, 2023a); the Single Event Upset Test Facility (SEUTF) at BNL (Brookhaven National Laboratory, 2023b); and FSEE, the new Single Event Effects test facility at the Facility for Rare Isotope Beams (FRIB) (Michigan State University, 2023a) at Michigan State University (MSU).

The TAMU facility is a part of the Association for Research of University Nuclear Accelerators (ARUNA) (ARUNA, 2023), which also includes the Fox Accelerator Laboratory at Florida State University (Florida State University, 2023), the Ion Beam Analysis Laboratory at Hope College (Hope College, 2023), the Edwards Accelerator Laboratory at Ohio University (Ohio University, 2023), the Triangle Universities Nuclear Laboratory (TUNL) at Duke University (Duke University, 2023), the Ion Beam Analysis Laboratory at Union College (Union College, 2023), the Radiation Laboratory at the University of Massachusetts-Lowell (University of Massachusetts Lowell, 2023), the Accelerator Laboratory at the University of Kentucky (University of Kentucky, 2023), the Institute for Structure and Nuclear Astrophysics (ISNAP) (University of Notre Dame, 2023) at the University of Notre Dame, and the Center for Experimental Nuclear Physics and Astrophysics (CENPA) (University of Washington, 2023) at the University of Washington. Since the other ARUNA facilities produce beams with maximum energies significantly lower than those at TAMU, they have not been used for space research to date.

There are other accelerators in the US that also have not been utilized for space research, including: the ATLAS facility (Argonne National Laboratory, 2023) at Argonne National Laboratory (ANL); the Relativistic Heavy Ion Collider (RHIC) (Brookhaven National Laboratory, 2023c) at BNL; the Continuous Electron Beam Accelerator Facility (CEBAF) (Jefferson Laboratory, 2023) at the Thomas Jefferson National Laboratory (JLab); the Spallation Neutron Source (SNS) (Oak Ridge National Laboratory, 2023) at Oak Ridge National Laboratory (ORNL); the Los Alamos Neutron Science Center (LANSCE) (Los Alamos National Laboratory, 2023a) and Weapons Neutron Research (WNR) facility (Los Alamos National Laboratory, 2023b) at Los Alamos National Laboratory (LANL); and the Tevatron (Fermilab, 2023) at Fermilab National Accelerator Laboratory (FNAL). Finally, there are some accelerators that have been decommissioned, including the K500 and K1200 cyclotrons at the National Superconducting Cyclotron Center (Michigan State University, 2023b) at MSU.

In Canada, the Proton Irradiation Facility (TRIUMF, 2023a) and Neutron Irradiation Facility (TRIUMF, 2023b) at Canada's National Particle Accelerator Center TRIUMF in Vancouver have been used for irradiation studies of electronic systems.

In Europe, nine accelerators in seven countries have been used for space research. These include: the Heavy Ion Facility (HIF) and Light Ion Facility (LIF) at the Universite Catholique de Louvain (UCL) (Universite Catholique de Louvain, 2023) in Louvain-la-Neuve, Belgium; the RADiation Effects Facility (RADEF) (University of Jyväskylä, 2023) at the Accelerator Laboratory at the University of Jyväskylä, Finland; the G4 facility at the Grand Accelerateur National d'Ions Lourds (GANIL) (GANIL, 2023) in Caen, France; the Heavy Ion Synchrotron SIS18 at the Gesellschaft fur ScherwIonenforschung (GSI) Helmholtz Centre for Heavy Ion Research (Durante et al., 2010) in Darmstadt, Germany; the INFN Southern National Laboratory (LNS) (INFN, 2023) in Catania, Italy; the Holland Proton Therapy Center (Fleury et al., 2021) in Delft, the Netherlands; the Keuring voor Ingebruikname (KVI) Center for Advanced Radiation Technology (KVI-CART) facility (Univ of Groningen, 2023) at the University of Groningen in the Netherlands; the CERN High energy AcceleRator Mixed field facility (CERN CHARM) (Alía et al., 2018) at CERN in Geneva, Switzerland; and the Proton Irradiation Facility (PIF) (Hajdas et al., 2001) at the Paul Scherrer Institute (PSI) in Switzerland.

In Asia, there are 28 accelerator facilities (Tanaka, 2020). While most of these are low-energy facilities, a number can produce beams of sufficiently high energy for space studies. These include: the Research Center for Nuclear Physics (RCNP) (Osaka Univ., 2015) at Osaka University in Osaka, Japan; the Japan Proton Accelerator Research Complex (JPARC) (KEK, 2018) in Tokai-Mura, Japan; the RIKEN Nishina Center (RIKEN, 2023) in Wako, Japan; the Heavy Ion Research Facility (HIRFL) (Chinese Academy of Sciences, 2023a) in Lanzhou, China; the Chinese Neutron Spallation Source (CSNS) (Chinese Academy of Sciences, 2023b) in Dongguan, China; the High Intensity Heavy-ion Accelerator Facility (HIAF) (Chinese Academy of Sciences, 2023c) in Huizhou, China; the Beijing RI beam Facility (BRIF) (Chinese Institute of Atomic Energy, 2023) in Beijing, China; and the RAON facility (Institute for Basic Science, 2023) in Daejeon, Korea.

Each of the facilities listed above have different maximum beam energies and intensities, detector stations, number of hours available for users, and specializations. What they have in common, however, is that the requests for beam time from users for space research significantly outstrips the availability. The space electronics effects community, for example, has requested twice the available beam across the relevant US facilities in 2022; that factor is expected to grow even larger in the coming decade. A portion of this demand could be met by repurposing existing accelerators that have become dormant, such as the aforementioned K500 and K1200 cyclotrons at MSU.

Understanding the effects of GCRs with the highest (well over GeV/u) energies is important to the space radiation protection community. However, with no measurements at projectile energies over 3 GeV/u, simulations of these effects lack an empirical foundation. Higher-energy measurements are also required to understand electronic effects in the latest circuits whose size is greater than the range of ions available at nearly all accelerators used in these studies so far. There is, however, a possibility to fill some of these critical nuclear data gaps by using the RHIC beams at BNL. A beam time proposal (Cebra, 2022) was recently made to bombard C, Al, and Fe targets with He, C, Si, and Fe ions at energies from 3–50 GeV/u, and to detect the light particle production (the "secondaries") with the STAR detector. This measurement, however, would have to be completed before the conversion of RHIC to the Electron-Ion Collider (EIC) (Khalek et al., 2021) project begins in ~2025.

An additional capability needed for space research accelerator measurements is a larger beam diameter. Traditional accelerators have beam spot diameters that are capable of irradiating one chip at a time. Rastering and defocusing techniques now enable some of the facilities mentioned above to irradiate batches of chips. However, laboratory measurements can more realistically reproduce the GCR damage inflicted in space by irradiating large, complex subsystems all at once. The special approaches needed to obtain such wide beam diameters while keeping uniform beam densities should be implemented at accelerators carrying out space-based research.

2.2 Databases, dissemination, compilation

At present, the primary means of disseminating nuclear reaction cross sections measurements relevant for space research is via journal publications. There are, however, two compilations of this data. The first is an online GSI—ESA—NASA database (Luoni et al., 2021) that contains 1786 data points from 110 peer-reviewed publications. The second is NUCDAT (Norbury and Miller, 2012; Norbury et al., 2020), a data collection that contains 50,000 entries. The coverage of relevant ions, bombarding energies, and targets in these databases is, however, a small fraction of the data needed for effective modeling of nuclear reactions for space effects.

It should be noted that neither of these collections were compiled in connection with the major nuclear data organizations, the IAEA Nuclear Data Service (Forrest, 2011; IAEA, 2023) and the US National Nuclear Data Center (NNDC, 2023). The international standard reaction databases for nuclear reaction data, EXFOR (Otuka et al., 2014) (for compilations) and ENDF (Brown et al., 2018) (for evaluations), have limited applicability for space research as they are focused on neutron-induced reactions at energies less than 14 MeV. They do, however, contain some cross sections up to 200 MeV and a few charged-particle induced reactions. Finally, the OECD NEA Shielding Integral Benchmark Archive and Database (SINBAD) (Kodeli et al., 2014) has some integral cross section information that is useful, such as a set containing measurements of 100–800 MeV/u He, C, Ne, Ar, Fe, Xe, and Si ions bombarding C, Al, Cu, and Pb targets.

There are also a number of specialized databases within the space electronics effects community, including (in the US) collections at NASA Goddard Space Flight Center (GSFC) (NASA GSFC, 2023) and NASA Jet Propulsion Laboratory (JPL) (NASA JPL, 2023). A number of factors have, unfortunately, impeded the coordination between these different collections, including the different systems measured, proprietary data, security, formats, and funding to initiate and (especially) maintain a more unified data library.

The current disjoint collections of nuclear and electronic effects datasets for space research could benefit tremendously from the decades of experience in the nuclear data community in establishing, curating, combining, and disseminating datasets. By linking these space-related datasets together and creating new customized collections, the nuclear data community could greatly improve access to the existing data that are so critical for simulations in space research studies. This effort would also be invaluable for guiding future experimental work as gaps in the measurement data could be more easily accessed.

2.3 Reaction models

Because all the nuclear cross sections needed for space research will never be measured, nuclear reaction models are critical for simulations that transport GCR primaries through spacecraft materials and predict the flux and composition of secondaries. Results of such transport simulations are subsequently utilized in studies of electronic effects (Höeffgen et al., 2020), human effects (Rajaraman et al., 2018; Walsh et al., 2019), and spacecraft design (Fukunaga et al., 1997). Nuclear reaction models are also essential to predict the yields, and therefore determine the viability of, accelerator-based measurements of reactions important for space research.

The space research community has had some successes with phenomenological nuclear reaction models. One notable example is the Double Differential Fragmentation model (DDFRG) (Norbury, 2021) which has been fine-tuned to agree with measurements in the NUCDAT collection (Norbury and Miller, 2012; Norbury et al., 2020) mentioned above. Other models include NUClear FRaGmentation (NUCFRG) (Wilson et al., 1987), which uses an abrasion–ablation formalism (Hüfner et al., 1975), and the self-consistent Relativistic Abrasion–Ablation FRaGmentation (RAADFRG) code (Werneth et al., 2021). Semi-empirical parameterizations (e.g., Hybrid Kurotama (Sihver et al., 2014), Kox-Shen (Kox et al., 1987)) have also shown reasonable agreement with some datasets, and a number of such formulations have been collected and put online in the GSI-ESA-NASA database (Luoni et al., 2021) mentioned above.

Even though most of the terms in reactions models at energies ranging from 0.1–1 GeV/u (including pre-equilibrium, de-excitation, evaporation, intra-nuclear cascade, fission, and more) are reasonably well understood, more data are needed to fine tune these models. For example, De Napoli et al. (2014) shows that the predictions of two microscopic models—Quantum Molecular Dynamics (QMD) (Aichelin, 1991) and Binary Light Ions Cascade (BLIC) (Folger et al., 2004)—for ^{4}He production via the ^{12}C + ^{12}C reaction at 62 MeV/u vary by a factor of 2. The phenomenological reaction parameterizations discussed in (Luoni et al., 2021) show that the variations in cross section predictions at 200 MeV/u can be as large as a factor of 2 for certain beam-target combinations (see Figure 15 in Luoni et al., 2021). For most systems the variations are, however, 25% or less. Figure 17 in Luoni et al. (2021) shows that variations of parameterization predictions at 10 GeV/u are typically 10%–25% when averaged over many models and systems. It is important to note, however, that these parameterizations are primarily benchmarked on data at a few hundred MeV/u, with only a few data points at 1 GeV/u, so these higher-energy extrapolations need measurements for validation (Luoni et al., 2021).

However, the state-of-the-art models of the highest energy reactions in the space community lag recent theoretical work being done in the RHIC community. While the former conceptualizes heavy ion reactions in terms of abrasion, ablation, and coalescence, the latter embraces models in which hadronic reaction products are constructed from quarks and gluons. A good example of such a RHIC-related model is the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) model (Bleicher et al., 1999). This model has demonstrated the capability to predict the yields of protons and deuterons measured at the BNL Alternating Gradient Synchrotron (AGS) from the bombardment of Be and Au targets with 15 GeV protons (Sombun et al., 2019). The utilization of this, and other, RHIC codes for predicting the yield of secondaries resulting from GCR transport through spacecraft materials would, when combined with additional higher-energy data, significantly advance the simulations needed to make space exploration safer.

The focus of this study has been on the need for a better understanding of interactions of GCR particles of energies above 0.2 GeV/u with spacecraft materials, electronics, and astronauts. Reactions at energies below 200 MeV/u are, however, relevant for the lowest energy GCRs as well as the end of cascades induced by higher-energy GCRs. To develop a comprehensive treatment of nuclear reactions for all GCRs, some improvements are also needed for these low energy interactions. For example, De Napoli et al. (2014) shows disagreements of up to a factor of 5 between measurements of ^{4}He production from ^{12}C + ^{12}C reaction at 62 A MeV and predictions from the popular QMD (Aichelin, 1991) and BLIC (Folger et al., 2004) models. Clearly more work is needed to improve the models at these energies, and to explain other effects that can contribute to light-ion production via fragmentation such as evaporation after incomplete fusion, deep-inelastic processes, and target fragmentation (De Napoli et al., 2014).

2.4 End-user applications

Some of the most critical end-user applications in space research include radiation transport simulations, electronics and human effects studies, and spacecraft design. Below we detail the current the state-of-the-art and relevant nuclear data gaps for each of these, with an emphasis on cross-disciplinary collaborative research efforts that can have a strong impact on space exploration.

2.4.1 Radiation transport

Modeling the transport of GCRs through spacecraft materials is needed to characterize the flux and composition of secondaries. The space science community has invested 30 years of development in HZETRN (High charge (Z) and Energy TRaNsport) (Wilson et al., 2014), a suite of deterministic (i.e., non-Monte Carlo) codes that numerically solve the Boltzmann transport equation in three dimensions. With NUCFRG (Wilson et al., 1987) as its core nuclear reaction model, 3DHZETRN can calculate GCR-induced radiation levels for a variety of simple shielding configurations. The latest 3D version of this code, 3DHZETRN, is orders of magnitude faster than Monte Carlo (MC) transport codes and has been extensively benchmarked in simple slab geometries. 3DHZETRN results compare favorably with three-dimensional MC package calculations (Norbury et al., 2017). It should be noted, however, that MC codes can simulate the complex shielding geometries that more realistically represent those used in spacecraft.

Other transport codes from the space community include HETC-HEDS (Charara et al., 2008), SHIELD (Norbury et al., 2019), and COMIMART-MC (Vicente-Retortillo et al., 2015). Related code systems include OLTARIS (On-Line Tool for the Assessment of Radiation In Space) (Sandridge et al., 2011), a web tool using HZETRN and NUCFRG to study the effects of space radiation on spacecraft, humans, and electronics, and PLANETOCOSMICS (ESA) (Desorgher, 2006) that uses GEANT code (mentioned below) for transport.

Transport simulations are also used throughout nuclear and particle physics, for applications ranging from accelerator shielding to thick-target isotope production to detector characterizations and calibrations to deciphering integral measurements. Some popular particle transport codes include FLUKA (Battistoni et al., 2015), PHITS (Sato et al., 2013), GEANT4 (Agostinelli et al., 2003), and MCNP (McKinney et al., 2006). These MC-based codes have built-in nuclear reaction models, optimized over different energy ranges, and some have options to adjust model parameters to the problem at hand. In many cases, users only need to specify the geometry of the "target" and the input radiation field, and the code package handles all the transport calculations. These transport codes have been validated through extensive comparison with integral experiments, with MCNP and GEANT validated primarily at lower energies, and FLUKA and PHITS at higher energies.

In an alternative approach, the RHIC community has extensive capabilities to simulate the production of light ions resulting from heavy ion collisions. While the RHIC codes are often used to extract QCD parameters from the central collision region, some codes (such as the UrQMD model described above) already have the capability to predict yields of light ions. With some adaptation, other RHIC codes may be helpful for modeling the interactions of the highest energy GCRs with spacecraft materials.

Finally, it may be advantageous for the space transport community to investigate the use of advanced computing approaches, including cloud computing, grid computing, machine learning, and computing acceleration with graphical processing units (GPUs). Higher computing power can enable more and more complex systems to be modeled to a higher degree of spatial and energy resolution. An example of one such approach (GPU acceleration) for human effects research (Wan Chan Tseung et al., 2015; Ma et al., 2020) is discussed below.

2.4.2 Electronics and human effects

Along with the energy deposition related to direct ionization, the secondaries generated by transport of the primary GCRs through spacecraft materials can disrupt and disable electronic systems and harm astronauts. Understanding these effects requires extensive modeling benchmarked by experimental measurements. Modeling with higher spatial fidelity is needed for both human effects and electronics effects. In electronics, the sub-micron size of the smallest features of the new, high-density systems is pushing a need for improved predictions of the species, angles, and energies of the produced secondaries. Such information, when combined with ion stopping power (the average energy deposition in a medium per unit path length dE/dx (L'Annunziata, 2003)), enables MC-based codes like MRED (Reed et al., 2015) to track these ions and their energy deposition within a chip. However, higher energy measurements are needed to probe the full physical range of the newest larger circuit elements and subsystems.

The push for finer spatial resolution in human effects modeling is driven by the need to more precisely inventory the damage that GCRs inflict at the sub-cellular level. Advances in ion-beam therapy for cancer patients on Earth are driving innovations that can benefit space effects research. An example is the development of a custom kernel for a nuclear reaction that includes terms for intranuclear cascade, particle evaporation, and non-elastic cross sections (Wan Chan Tseung et al., 2015; Ma et al., 2020).

This model shows very good agreement with measurements of, for example, 200 MeV protons bombarding ^{16}O targets. Planned improvements to this approach include expanding the physics models to accommodate GeV energies and heavier ions and shrinking the spatial resolution of the model (when combined with transport through human tissue) from a cell to a molecule, i.e., by a factor of 10^2–10^3. In order to achieve such improvements, the kernel will be ported to GPUs to enable the use of high performance computing (HPC) resources. A first effort to port the existing kernel has already resulted in transport simulations running 200 times faster than an equivalent simulation with GEANT4. When coupled to tissue-damage codes as described below, this effort has the potential to significantly improve the fidelity of models predicting sub-cellular damage in humans resulting from bombardment by GCRs, and therefore to eventually improve the safety of human space exploration.

Two noteworthy studies of tissue damage involve coupling GEANT4 to biological simulations. One is the GEANT4-DNA code, a low-energy extension of GEANT4 that enables studies of the cellular radiobiological effects of ionizing radiation on DNA, considering the physical, chemical, and biological stages of the interactions. GEANT4 has also been coupled to the CompuCell3D cell biology simulation platform via the RADCELL module (Liu et al., 2021), enabling tumor geometries to be ported to the transport code. The ion stopping powers in various materials are key inputs for these codes. A widely used code to calculate these stopping powers is SRIM (Ziegler et al., 2010).

2.4.3 Spacecraft design

The design of a spacecraft (Fukunaga et al., 1997) must carefully fold together details of the mission objective, payload instruments and plan, and the subsystems to support the payload including power, propulsion, structure, communications, data handling, and more. Because many of the requirements of different subsystems will conflict, optimization plays a critical role in the overall design. Nuclear physics and spacecraft design overlaps in the area of radiation protection. As noted above, the shielding to reduce the GCR flux is also a target that influences the flux of secondaries, with thicker shielding also impacting the structure and propulsion design (Warden and Bayazitoglu, 2021).

Two of the major uncertainties in shielding design are the space radiation environment itself and incomplete information for radiation transport calculations. In the first case, the changes in the space environment over the duration of a mission must be quantitatively estimated. In the second case, realistic radiation transport requires the best transport codes, along with accurate inputs of the radiation environment, all available relevant nuclear data for all particle interactions, and information on stopping powers to better assess damage to electronic systems and astronauts caused by the deposited energy. Gaps in our knowledge, especially related to nuclear data, are discussed above for most of these issues—cross sections, nuclear reaction models, transport codes, experimental measurements for code benchmarking, and energy deposition studies. The challenge to the spacecraft designer is to balance conflicting requirements between different spacecraft subsystems to arrive at an optimal configuration (Fukunaga et al., 1997).

Recently, work has focused on improving radiation transport modeling, both by more refined codes and, especially, by improving the nuclear physics input. The previous section detailed the motivations for enhancing the spatial resolution of transport models to simulate the effects of GCR impact on electronics and astronauts: the need to study higher density circuit elements with spatially smaller features and the desire to model sub-cellular tissue damage. Other critical areas of investigation in this field are sensitivity studies and uncertainty quantification; these are described in the following subsection.

Finally, significant advances are being made in other fields such as in the development of surrogate models and in dimensional reduction within a machine learning (ML) framework for optimizing model predictions across enormous parameter spaces. The application of such approaches, especially if combined with GPU acceleration and the use of HPC resources, could significantly advance the design of safer spacecraft.

2.5 Sensitivity studies and uncertainty quantification

To identify the most critical nuclear data gaps in space research, it is necessary to examine the quantitative variation in space model predictions that arise from variations in nuclear physics inputs. One approach is to utilize different nuclear model inputs in the same transport code. An example of this is shown in Figure 2 of Norbury et al. (2020), where QMD (Aichelin, 1991) and INCLXX (CEA, 2014) models, used as input to GEANT4 transport calculations, produce differences in light-ion production of up to a factor of 3 at energies below 10 GeV/u. Another approach, also shown in the same figure from Norbury et al. (2020), is to utilize different transport codes with different nuclear inputs; this produces light-ion production variations of up to a factor of 20 over the same energy range. These approaches can be used to quantify the overall contribution of cross section libraries, or that of the combination of cross sections and transport codes, to the uncertainty of the predictions of these models.

With such approaches, it is not possible to identify specific reactions giving the largest impact on the transport calculation predictions because entire libraries of input cross sections are changed. An alternate approach is a “sensitivity study” where only one reaction cross section is systematically changed in each calculation. While sensitivity studies are not commonly used in space research, one study has shown the importance of cross sections for p, n, and α particle production under bombardment by specific ions (e.g., O, Mg, Si, Fe) (Lin, 2007). In another study, the impact of cross section changes on dose equivalent was made as a function of shielding depth, see Lin and Adams (2007), using the HZETRN transport code. Changes of 25% in the input cross sections at 0.3 GeV/u were found in that study to produce 10% changes in the output dose equivalent predictions. An energy survey in the same study found that cross section changes in the 0.2–1.5 GeV/u energy range were the most impactful on the dose equivalent predictions. It is important to note that the 25% cross section variations used in Lin and Adams (2007) are representative of cross section uncertainties at 0.3 GeV/u (Luoni et al., 2021) but could underestimate the uncertainties at higher energies where there are few measurements.

The effects of GCRs on integrated circuits were estimated in Ref. Dodd et al. (2007) using ground-based tests at typical energies of 10 MeV/u. It was shown that the rate of single-event effects that occur in space at the higher energies (~1 GeV/u) of GCRs may be significantly underestimated because higher energy GCRs generate secondary ions within the integrated circuits that penetrate more deeply into the circuits. The number of single-event effects per unit time can, in general, vary by up to five orders of magnitude depending on the radiation hardening of the circuit, the interaction cross sections, and other effects.

The decades of experience with sensitivity studies in the nuclear data community suggest that critical advances can be made in space science through collaborative, cross-disciplinary efforts. Some of the existing sensitivity tools in the nuclear data community include: TSUNAMI, TSAR, SEN3, and SAMPLER (ORNL) (Perfetti and Rearden, 2013); Whisper and Crater (LANL) (Kiedrowski et al., 2015); Nuclear Data Sensitivity Tool (NDaST) (OECD NEA) (Dyrda et al., 2017); SUSD3D (JAEA/NEA) (Kos et al., 2021); NUSS-RF (PSI) (Zhu et al., 2015); FICST (McMaster University) (Mostofian, 2014); RMC (Tsinghua University) (Wang et al., 2014); and GPT-free in OpenMC (MIT/Purdue/Virginia Commonwealth University) (Wu et al., 2019). While many of these codes were designed specifically to determine the sensitivities of input nuclear cross sections on nuclear reactor performance (such as the effective neutron multiplication factor k_{eff}) and for nuclear criticality safety studies, some are more general and could potentially be adopted to address sensitivities critical for space research.

Sensitivity studies can be used to translate the uncertainties on the model inputs into uncertainties on the model predictions. While uncertainty quantification (UQ) approaches in general have been a high priority in the nuclear data community, they are not widely adopted in the space research community. The combination of Bayesian approaches with ML tools have recently begun to set the standard for assigning uncertainties to model predictions in the nuclear science community (see, for example, Neufcourt et al., 2018). Collaborative efforts between the two communities could, for example, enable nuclear cross section uncertainties to be propagated through transport models to uncertainties in the secondary flux characteristics, and subsequently propagated through specialized codes to assess uncertainties in electronics and tissue damage.

Combining such UQ approaches with sensitivity studies can then guide future work in measurements, nuclear reaction theory, transport models, and stopping power codes. Currently under development, EUCLID (LANL) will be the first of a new generation of tools in the nuclear data community that uses this combined approach for reactors or critical systems. EUCLID is an extension of work using ML to improve nuclear data validation (Neudecker et al., 2020). By combining sensitivity studies, uncertainty quantification, nuclear dataset adjustment, and ML-driven design of experimental measurements, this tool will be able to identify which new measurements would provide the tightest constraints on predictions for an end-user application. A EUCLID-like tool for the space research community could be used to assign uncertainties to model predictions, identify critical data and theory gaps, and recommend approaches to best fill those gaps.

3 Discussion

Simulations of the flux of GCR secondaries in spacecraft depend on nuclear reaction cross section measurements and theoretical models, as well as on transport codes and spacecraft materials. The harmful effects of these secondaries subsequently depend on their composition, energy, angles of incidence, and stopping powers in a wide range of electronic devices and human tissue. To make space exploration missions viable and safe, spacecraft designers must optimize shielding configurations that minimize these harmful effects over the duration of a mission with its changing radiation environment and this optimization must handle conflicting constraints imposed by the other major subsystems of the vessel.

An “ideal” inventory of the tools and data needed for such space studies can be envisioned. This could include, for example, a complete set of reaction cross sections with uncertainties for the generation of light-ion secondaries (with high-fidelity energy and angle information) from light- and heavy-ion bombardment, at energies up to ~50 GeV/u. Also critical would be a radiation transport code with fine spatial resolution that can handle complex shielding material configurations and that can generate uncertainties in secondary energies and angles from input nuclear data uncertainties. Additionally, simulations are needed that can determine the harmful energy deposition of secondaries, along with uncertainties propagated from input uncertainties, in electronic devices (human tissue) at the sub-micron (sub-cellular) level. Codes that can perform the simulations described above in a time-dependent radiation field, and can optimize spacecraft subsystem design within propagated uncertainties, would be an essential part of this inventory. Finally, the connection to nuclear data can be made with codes using sensitivity analysis techniques at each of the above steps; this would enable the most critical nuclear data to be identified and recommend measurement approaches.

Developing these tools and datasets will require significant efforts, especially the measurements at higher energy and the uncertainty propagation through the wide variety of simulations. However, given the expertise of the nuclear data community in these areas, some progress towards these “ideals” can be made by collaborative cross-disciplinary research efforts. Regarding experimental efforts, the STAR detector at RHIC could be used to measure some unique data at higher energies than currently available; beam time requests at accelerators could be coordinated, as could plans to effectively re-use dormant accelerators; approaches for compiling, disseminating, archiving, and managing data from accelerator measurements for space research could be borrowed from the nuclear data community; and nuclear reaction models developed in the RHIC community could be modified to significantly advance predictions of unmeasured reactions at high energies. Regarding computational and modeling projects, HPC resources for MC-based transport codes could be utilized to enable transport simulations with complex shielding material configurations; transport codes could be ported to GPUs and, with HPC systems, enable the higher spatial fidelity simulations needed for modern electronic devices and sub-cellular damage assessments; ML approaches like surrogate models could be used for the optimization in spacecraft design; and a EUCLID-type

ML-driven code could be developed for space science to automate sensitivity studies, identify nuclear data outliers, and recommend new experiments.

4 Summary

The discussions here highlight the many overlaps between space science and nuclear science that can be expanded upon to study the effects of the broad range of GCR energies and species on electronics and humans. By effectively exploiting these overlaps, progress can be made in improving vessel design to make space exploration safer and more viable for humans.

Some of the most fertile topics for collaborative work include: making additional cross section measurements with high energy ions, especially using the STAR detector at RHIC; coordinating accelerator beam time requests; borrowing approaches from the nuclear data community for the compilation, dissemination, archiving, and management of nuclear data; utilizing advances in nuclear reaction theory by the RHIC community for modeling reactions important for GCR secondaries; and adopting UQ, sensitivity analyses, ML approaches, and HPC resources to better model highly complex space systems with proper uncertainty propagation.

Through these cross-disciplinary, collaborative research projects, the state-of-the-art in space research could be significantly advanced, resulting in safer space exploration.

Author contributions

MS, RV, and KL contributed to conception and scope of this review. MS wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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