

Nuclear Data for High Energy Ion Interactions and Secondary Particle Production



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Table of Contents

ABSTRACT	5
I. INTRODUCTION	6
II. BACKGROUND	6
III. CURRENT STATUS AND NUCLEAR DATA GAPS	8
<i>A. Experimental Facilities</i>	8
<i>B. Databases, Dissemination, Compilation</i>	10
<i>C. Reaction Models</i>	11
<i>D. End-User Applications</i>	12
<i>1. Radiation Transport</i>	13
<i>2. Electronics and Human Effects</i>	14
<i>3. Spacecraft Design</i>	15
<i>E. Sensitivity Studies and Uncertainty Quantification</i>	16
IV. DISCUSSION	17
V. SUMMARY	19
VI. ACKNOWLEDGEMENTS	19
REFERENCES	20

Abstract

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.

I. INTRODUCTION

Nuclear data has a wide range of utilizations, both in basic research and in applied fields. In recent years, a series of meetings – the Workshop on Applied Nuclear Data Activities (WANDA) [1–5] – 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.

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. At the WANDA 2022 meeting [6], three 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 of the secondary radiations generated by those interactions.

After giving some background in Section II of this report, we will detail the current status and nuclear data gaps in experiments, databases, dissemination, compilation, reaction models, radiation transport, electronics effects, human effects, spacecraft design, sensitivity studies, and uncertainty quantification in Section III. In Section IV, 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 V.

II. BACKGROUND

The wide range of energies (up to $\sim\text{TeV}$) and species ($Z\sim 1 - 28$) of GCRs [7] 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, 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 [8], 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 [9].

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 [10] (for example, aluminum, polyethylene, and composites) to generate a complex cascade of secondary radiation (light ions, neutrons, gamma rays) [11] which can further harm astronauts and disrupt or disable electronic systems (Fig. 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.

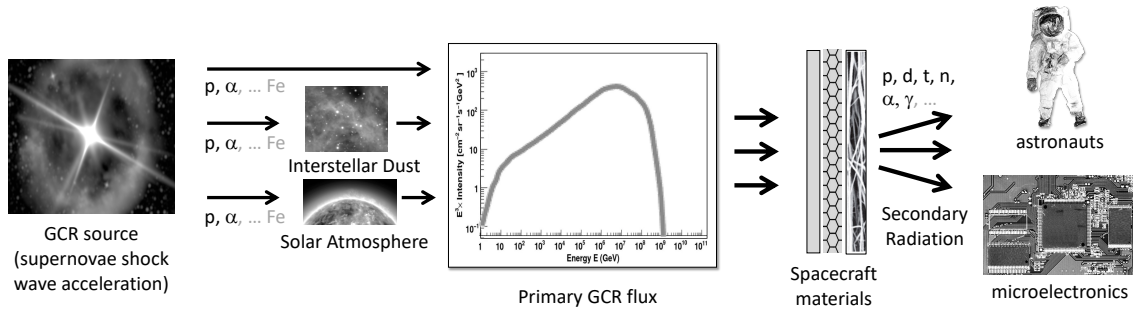


FIG. 1: Primary and secondary galactic cosmic rays (GCR).

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 such as nuclear reaction cross sections. This is an area of specialization of the nuclear data community, and requires a number of activities – in experimental measurements, compilation, evaluation, databases, dissemination, reaction modeling, and uncertainty quantification. These activities are generally described as the “nuclear data pipeline” [12] (Fig. 2), 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, we provide the current status and identify the nuclear data gaps in portions of the nuclear data pipeline that are relevant for space exploration.

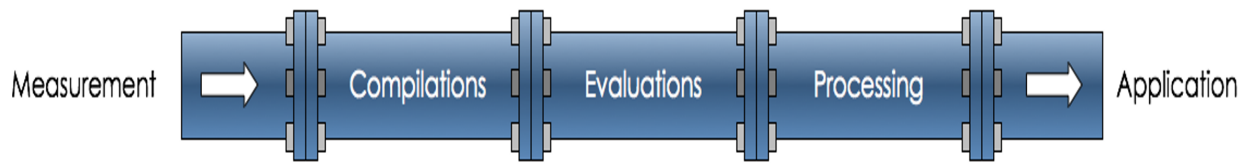


FIG. 2: The nuclear data pipeline.

III. 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.

A. 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) [13]; the Berkeley Accelerator Space Effects (BASE) facility at Lawrence Berkeley National Laboratory (LBNL) [14]; the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory (BNL) [15]; the Single Event Upset Test Facility (SEUTF) at BNL [16]; and FSEE, the new Single Event Effects test facility at the Facility for Rare Isotope Beams (FRIB) [17] at Michigan State University (MSU).

The TAMU facility is a part of the Association for Research of University Nuclear Accelerators (ARUNA) [18], which also includes the Fox Accelerator Laboratory at Florida State University [19], the Ion Beam Analysis Laboratory at Hope College [20], the Edwards Accelerator Laboratory at Ohio University [21], the Triangle Universities Nuclear Laboratory (TUNL) at Duke University [22], the Ion Beam Analysis Laboratory at Union College [23], the Radiation Laboratory at the University of Massachusetts-Lowell [24], the Accelerator Laboratory at the University of Kentucky [25], the Institute for Structure and Nuclear Astrophysics (ISNAP) [26] at the University of Notre Dame, and the Center for Experimental Nuclear Physics and Astrophysics (CENPA) [27] 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 [28] at Argonne National Laboratory (ANL); the Relativistic Heavy Ion Collider (RHIC) [29] at BNL; the Continuous Electron Beam Accelerator Facility (CEBAF) [30] at the Thomas Jefferson National Laboratory (JLab); the Spallation Neutron Source (SNS) [31] at Oak Ridge National Laboratory (ORNL); the Los Alamos Neutron Science Center (LANSCE) [32] and Weapons Neutron Research (WNR) facility [33] at Los Alamos National Laboratory (LANL); and the Tevatron [34] 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 [35] at MSU.

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) [36] in Louvain-la-Neuve, Belgium; the RADiation Effects Facility (RADEF) [37] at the Accelerator Laboratory at the University of Jyväskylä, Finland; the G4 facility at the Grand Accelérateur National d'Ions Lourds (GANIL) [38] in Caen, France; the Heavy Ion Synchrotron SIS18 at the Gesellschaft für Schwerionenforschung (GSI) Helmholtz Centre for Heavy Ion Research [39] in Darmstadt, Germany; the INFN Southern National Laboratory (LNS) [40] in Catania, Italy; the Holland Proton Therapy Center [41] in Delft, the Netherlands; the Keuring voor Ingebruikname (KVI) Center for Advanced Radiation Technology (KVI-CART) facility [42] at the University of Groningen in the Netherlands; the CERN High energy Accelerator Mixed field facility (CERN CHARM) [43] at CERN in Geneva, Switzerland; and the Proton Irradiation Facility (PIF) [44] at the Paul Scherrer Institute (PSI) in Switzerland.

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) 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 [45] was recently made to bombard C, Al, and Fe targets with He, C, Si, and Fe ions at energies from 3 – 50 GeV, 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) [46] 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.

B. 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 [47] that contains 1786 data points from 110 peer-reviewed publications. The second is NUCDAT [48, 49], 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 both of these collections were not compiled in connection with the major nuclear data organizations, the IAEA Nuclear Data Service [50, 51] and the US National Nuclear Data Center [52]. The international standard reaction databases for nuclear reaction data, EXFOR [53] (for compilations) and ENDF [54] (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) [55] 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) [56] and NASA Jet Propulsion Laboratory (JPL) [57]. 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 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.

C. 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 [58], human effects [59, 60], and spacecraft design [61]. Nuclear reaction models are also essential to predict the yields, and there-

fore 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) [62] which has been fine-tuned to agree with measurements in the NUCDAT collection [48, 49] mentioned above. Other models include NUClear FRaGmentation (NUCFRG) [63], which uses an abrasion–ablation formalism [64], and the self-consistent Relativistic Abrasion–Ablation FRaGmentation (RAADFRG) code [65]. Semi-empirical parameterizations (*e.g.*, Hybrid Kurotama [66], Kox-Shen [67]) 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 [47] mentioned above.

Even though at energies ranging from 0.1 – 1 GeV/u, most of the terms in reactions models (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. However, the state-of-the-art models of the highest energy reactions in the space community lag recent 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 [68]. 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 [69]. 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.

D. 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.

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) [70], a suite of deterministic (*i.e.*, non-Monte Carlo) codes that numerically solve the Boltzmann transport equation in three dimensions. With NUCFRG [63] 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 [71]. 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 [72], SHIELD [73], and COMIMART-MC [74]. Related code systems include OLTARIS (On-Line Tool for the Assessment of Radiation In Space) [75], a web tool using HZETRN and NUCFRG to study the effects of space radiation on spacecraft, humans, and electronics, and PLANETOCOSMICS (ESA) [76] 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 [77], PHITS [78], GEANT4 [79], and MCNP [80]. 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 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 [81, 82] is discussed below.

2. *Electronics and Human Effects*

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 [83]), enables MC-based codes like MRED [84] 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 [81, 82]. 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 [85], 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 [86].

3. Spacecraft Design

The design of a spacecraft [61] 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 [87].

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 [61].

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 advance the design of safer spacecraft.

E. Sensitivity Studies and Uncertainty Quantification

One method to identify the most critical nuclear data gaps in space research is to determine the quantitative variation in space model predictions that arise from variations in nuclear physics inputs. Such “sensitivity studies” can also be used to quantify the uncertainty of the predictions of these space models, which subsequently enable reliable assessments of the safety of space missions. 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 particular (*e.g.*, O, Mg, Si, Fe) ions [88]. More such studies need to be done to cover the full range of the physics input to models of GCR damage.

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) [89]; Whisper and Crater (LANL) [90]; Nuclear Data Sensitivity Tool (NDaST) (OECD NEA) [91]; SUS3D (JAEA/NEA) [92]; NUSS-RF (PSI) [93]; FICST (McMaster University) [94]; RMC (Tsinghua University) [95]; and GPT-free in OpenMC (MIT/Purdue/Virginia Commonwealth University) [96]. While many of these codes were designed specifically to determine the sensitivities of input nuclear cross sections on nuclear reactor perfor-

mance (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, Ref. [97]). 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 [98]. 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.

IV. DISCUSSION

Simulations of the flux of GCR secondaries in spacecraft depends 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. 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.

V. 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.

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