

GSI-ESA-NASA Nuclear Cross-Section Database: Update I.

Addition of Proton-Projectile Reaction Cross-Sections

Francesca Luoni¹, Reka Szabo^{2,3}, Daria Boscolo², Charles Werneth⁴

Abstract: Nuclear reaction cross-sections are needed for Monte Carlo and deterministic radiation transport codes used for ion therapy and radiation protection in space. A GSI-ESA-NASA combined effort generated a free and publicly-available nucleus-nucleus reaction cross-section database. Nevertheless, protons—the main component of solar particle events and galactic cosmic ray fluences in space—account alone for over 60% of the effective dose behind thick shields in space and are used in 88% of the cancer-treatment ion-therapy centers worldwide. Therefore, in the present work, proton-projectile data have also been included. These data are compared to the reaction cross-section models used in radiation transport codes, including the models of Tripathi-Cucinotta-Wilson, Hybrid-Kurotama, Kox, Shen, and Kox-Shen. The Tripathi-Cucinotta-Wilson model uses the Tripathi99 model for low-Z projectile ions and the Tripathi96 model for other projectiles. The Hybrid-Kurotama model is based on the Black Sphere formula at high energies that is smoothly connected to the Tripathi99 model at low energies. It is found that the Tripathi99 and Hybrid-Kurotama models best fit the proton-projectile data.

Keywords: space exploration, radiation protection in space, shielding in space, ion therapy, nuclear reaction cross-sections, proton-projectile cross-sections

¹ Analytical Mechanics Associates, Hampton, VA (US)

² GSI Helmholtz Center for Heavy-Ion Research, Darmstadt (Germany)

³ Budapest University of Technology and Economics (Hungary)

⁴ NASA Langley Research Center, Hampton, VA (US)

1. Introduction

Human spaceflight is expected to flourish in the future with missions beyond low-Earth orbit including the Moon, Mars, and deep space. Among the many human health hazards associated with spaceflight are the low-gravity environment, isolation and confinement, distance from Earth, hostile environment, and space radiation (Afshinneko et al. (2020)). Space radiation is a complex mixture of high linear-energy-transfer (LET) radiation that arises from Solar Energetic Particles (SEPs) and Galactic Cosmic Rays (GCRs). SEPs are mostly composed of protons with energies that reach several hundred MeV and higher, whereas GCRs are composed of mostly protons and heavier nuclei with energies that reach TeV/u and higher (Benton and Benton (2001)). All but the most energetic SEPs are mitigated with passive shielding employed in spacecraft (National Research Council (2008), Washburn et al. (2015), Slaba et al. (2017)) while higher energy GCRs penetrate deeply into the vehicle and human tissue and represent a significant shielding challenge for space agencies and crewmembers (Luoni et al. (2022)).

In addition to space applications, ion radiation in the energy range of tens to a few hundred MeV/u is widely used in ion therapy. These two fields share many similarities (Tinganelli et al. (2021)). Particle therapy has emerged as a highly effective cancer treatment. Charged nuclei exhibit a favorable depth-dose distribution in the human body due to the Bragg peak, allowing for precise radiation delivery to tumors while minimizing exposure to healthy tissues compared to conventional radiotherapy (Durante and Haberer (2024)). This rapidly expanding field is growing worldwide, with 124 proton therapy centers and 17 carbon-ion therapy centers currently in operation, and many more in the planning and construction phases⁵.

Protons are crucial in both the fields of radiation protection in space and ion therapy. Protons are a major concern for space radiation exploration because of their large relative abundance. GCRs consist of approximately 2% electrons and 98% baryons, where the baryonic component comprises 85% protons, 14% helium nuclei, and 1% heavier ions (Chancellor et al. (2014)). Protons are produced copiously in solar particle events and are the main contributor to trapped particle radiation exposure for crew members during low-Earth orbit missions. Behind thick shielding configurations, such as the International Space Station (approximately 2-1000 g/cm², Koontz et al. (2005), Slaba et al. (2013)) and spacecraft that may be used for near-future Moon and Mars missions, protons and helium ions become the most relevant for dose and dose equivalent contributions (Norbury et al. (2020)). In particular, it was calculated that, behind a 20 g/cm² aluminium shield, 68% of the total effective dose is due to protons (Slaba and Blattnig (2014)). This number increases to 70% behind a 40 g/cm²

⁵ ptcog.site/index.php/facilities-in-operation-publication

aluminium shield. These predictions are also supported by Geant4 calculations (Norbury et al. (2020)).

The importance of proton nuclear interactions in therapy mirrors the rationale for space radiation protection. In carbon-ion therapy, protons are the most abundant secondary projectiles produced during projectile fragmentation processes. These protons contribute to both the lateral and longitudinal spread of the beam, particularly in the tail region beyond the Bragg peak. Therefore, their contribution to the final dose and radiobiological effects must be carefully considered in beam transport calculations as well as in treatment planning and optimization (Durante and Paganetti (2016)). In contrast, proton therapy primarily involves target fragmentation, predominantly generating secondary protons and neutrons. These target fragments, typically low in energy and thus high in LET, contribute to a fragmentation-induced buildup effect in the proton beam entrance channel. While their impact on physical dose and primary proton beam attenuation is already included in treatment planning softwares, recent studies suggest that more accurate descriptions of their production yields and energy spectra within the relevant energy range could enhance radiobiological dose estimations, particularly in the entrance channel (Bellinzona et al. (2021)).

Reliable radiation transport codes are used for risk assessment tools; space radiation shielding design; and optimization and safety of ion therapy. The particle fluences produced from the radiation transport codes require validated nuclear cross-section models (Townsend et al. (2002), Norbury et al. (2012), Luoni (2023a)) that are essential for providing the mean free paths for the interactions of GCR and SEP radiation with passive shielding in spacecraft and human tissues, and therapeutic ion beam interactions with passive modulators in clinical applications. Many radiation transport codes exist and are also used for other endpoints, spanning from particle accelerator research, to particle, nuclear physics, and astrophysics applications (Norbury et al. (2012)).

Several studies (Slaba et al. (2020), Luoni et al. (2022), Luoni et al. (2025)) that compared the doses of various Monte Carlo and deterministic radiation transport codes reveal that differences in the results are largely due to the variation of the nuclear cross-section models utilized. Consequently, nuclear cross section databases are essential for determining the veracity of the cross-section models to ensure particle doses are accurate.

In a previous study, a cross section database for nucleus-nucleus reactions was assembled through combined effort of GSI (Gesellschaft fuer Schwerionenforschung—Society for Heavy-Ion Research), ESA (European Space Agency), and NASA (National Aeronautics and Space Administration) (Luoni et al. (2021)). This database augmented a previous work (Norbury et al. (2011), Norbury et al. (2012)) and is accessible online from the GSI website⁶. Additionally, the experimentally measured data collected in the database were used to benchmark the reaction cross-section models used in radiation transport codes. The models are: Tripathi-Cucinotta-

⁶ <https://www.gsi.de/fragmentation>

Wilson, Kox, Shen, Kox–Shen, and Hybrid-Kurotama. An optimization of the Tripathi-Cucinotta-Wilson model was proposed (Luoni et al. (2023b)) to fit experimental data more accurately than the legacy models studied. The impact of this optimization on the Hybrid-Kurotama model was also evaluated, as it makes use of the Tripathi-Cucinotta-Wilson model at low energies.

The present work focuses on updating the nuclear reaction cross section database to include proton-nucleus reactions therefore providing additional opportunity for the assessment of nuclear model accuracy.

2. Addition of Proton-Projectile Data to the GSI-ESA-NASA Nuclear Reaction Cross-Section Database

As explained in Section 1, proton-projectile data are crucial in both the fields of radiation protection in space and ion therapy. Therefore, proton-projectile data have been added to the GSI-ESA-NASA reaction cross-section database.

Within the scope of this work, 1008 total reaction cross-section proton-projectile data were added to the original database from 53 publications (Cassels and Lawson (1954), Millburn et al. (1954), Chen et al. (1955), Burge (1959), Gooding (1959), Meyer and Carlson (1960a), Meyer and Hintz (1960b), Albert and Hansen (1961), Greenlees and Jarvis (1961), Johansson et al. (1961), Carlson et al. (1962), Goloskie and Strauch (1962), Wilkins and Igo (1963), Giles and Burge (1964), Makino et al. (1964), Turner et al. (1964), Bearpark (1965), Bulman et al. (1965), Dell et al. (1965), Makino et al. (1965a), Makino et al. (1965b), Pollock and Schrank (1965), Kirkby and Link (1966), Chapman and Macleod (1967), Dicello et al. (1967), Bulman and Griffith (1968), Hojvat and Jones (1968), Dicello and Igo (1970), Menet et al. (1971), Bertini (1972), Nicholls et al. (1972), Renberg et al. (1972), Bertrand and Peelle (1973), Montague et al. (1973), McGill et al. (1974), Carlson et al. (1975), Slaus et al. (1975), Sourkes et al. (1976), Davison et al. (1977), Jaros et al. (1978), Nasr et al. (1978), Abegg et al. (1979), Anderson et al. (1979), Segel et al. (1982), McGill et al. (1984), Carlson et al. (1985), McCamis et al. (1986), Carlson et al. (1994), Singh et al. (1994), Carlson et al. (1995), Eliyakut-Roshko et al. (1995), Carlson (1996), Enke et al. (1999)).

The original database had 1786 cross-section data from 103 publications (Luoni et al. (2021) and references within). Consequently, the database now contains 2794 data points from 156 publications. The publication criteria are the same as for the original database (Luoni et al. (2021)).

In the database, the experimental error bars were taken from the original publications. Some authors only report statistical errors, some also systematic uncertainties, in which case a combination of the two was evaluated (Luoni et al. (2021)). The error type was specified in the database for each data point. If multiple measurements were performed with the same experimental setup, the average cross-section was

calculated, and its uncertainty was derived by propagating statistical and systematic errors.

Fig. 1 reports the number of reaction cross-section data points included in the GSI-ESA-NASA cross-section database as a function of the projectile atomic number, Z_p , before and after the addition of proton-projectile data points. Reaction cross-sections refer to the probability that a non-elastic nuclear reaction will occur. Charge-changing cross-sections refer to the probability for the projectile nucleus to undergo a nuclear reaction that changes its atomic number. Therefore, reactions that change only its mass number e.g., neutron stripping, are a subgroup of reaction cross-sections, but not of charge-changing cross-sections (Luoni et al. (2021)). Fig. 1 is limited to projectiles up to nickel where thereafter particle fluences in the space radiation environment contribute negligibly to dose; likewise, nuclei with masses greater than nickel have not been used frequently for radiation therapy. The data referring to $Z_p=1$ before the addition of proton-projectile data, are mostly for deuteron-projectiles. Proton-projectile data are more abundant than any other projectile (Szabo (2023)). All proton-projectile data in this database are composed of reaction cross-sections (green in Fig. 1b).

In Fig. 2, the proton-projectile reaction cross-section entry numbers are shown as a function of the atomic number of the target nuclei. Specific targets are useful for endpoints spanning from nuclear engineering to nuclear physics, planetary physics, and astrophysics.

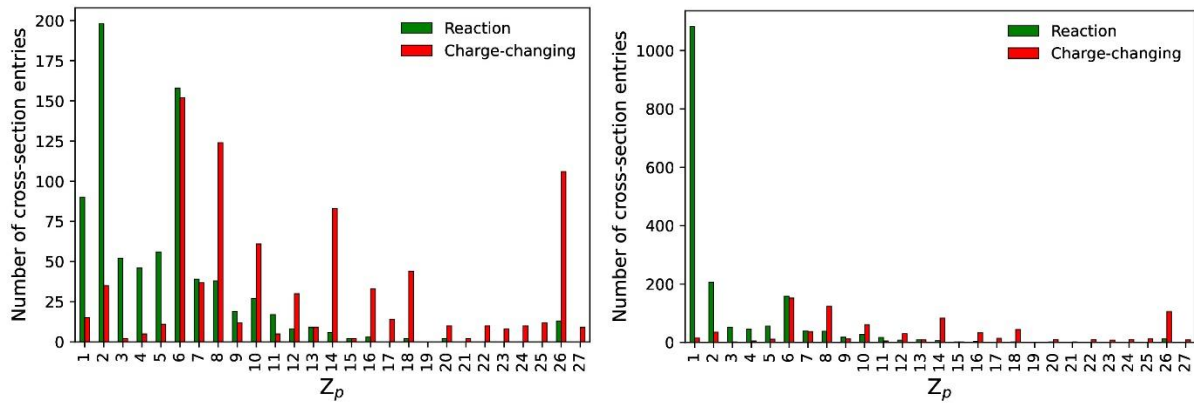


Figure 1: Number of cross-section data points in the reaction cross-section database as a function of the atomic number of the projectile nucleus, Z_p , before (Fig. 1a) and after (Fig. 1b) the addition of proton data. Charge-changing cross-section entry numbers are shown in red and reaction cross-sections are in green. Entries up to nickel projectiles only are reported.

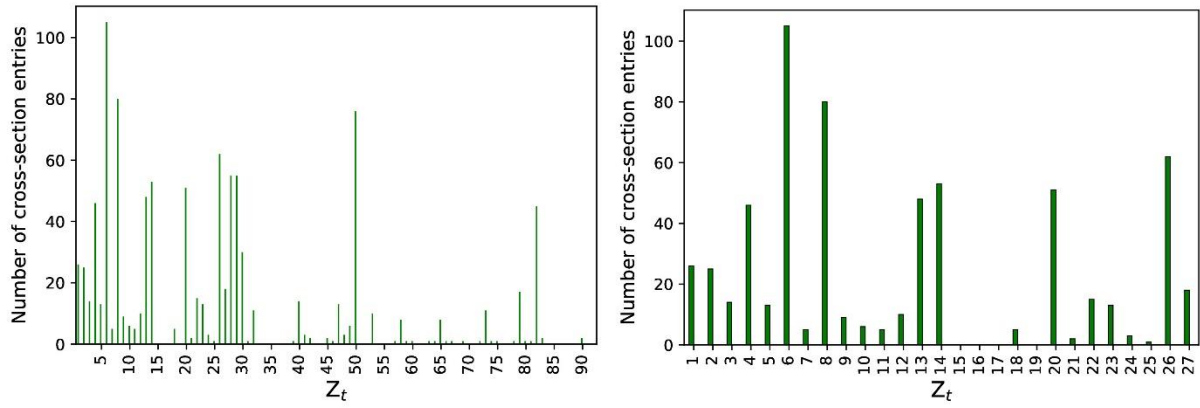


Figure 2: Number of proton-projectile reaction cross-section data added to the database as a function of the target atomic number. Fig. 2a shows all targets used for proton-projectile measurements. Figure 2b is a closed-up view on targets up to nickel, which correspond to the data of interest for space and therapy applications.

3. Comparison of the Collected Data with the Models Used for Radiation Transport Codes

The target nuclei of primary interest for space are as follows: ^1H , ^7Li , ^{12}C , ^{16}O , ^{27}Al , and ^{28}Si (Luoni et al. (2022)). ^1H , ^{12}C , and ^{16}O are the main constituents of the human body, and ^{27}Al is utilized as spacecraft structural material. Electronic instrumentation comprises ^{28}Si , and SiO_2 is the main constituent of Moon and Mars regolith, which can be used as *in situ* additional shielding. Lithium-based hydrides, mainly composed of ^1H and ^7Li are potential innovative shielding materials that have been tested through simulations and experiments. ^1H and ^{12}C are the main components of the well-established shielding material polyethylene. Finally, H_2O is a so-called dual-use shielding material to be used during the interplanetary flights.

The target nuclei of primary interest for ion-therapy are: ^1H , ^{12}C , and ^{16}O , since they are the main constituents of the human body. ^1H , ^{12}C , and ^{16}O are also common in materials composing passive modulators, which are positioned between the particle beam and the patient (Mohan and Grosshans (2017)).

Since ^1H is also an important target nucleus, proton-projectile cross-section data can also be used to evaluate inverse kinematic (IK) cross-sections of other ions reacting with proton-targets. The IK notation means that the projectile and target frames are reversed. Reaction cross-sections are conserved when the same kinetic energy per nucleon of the projectile and target are used after transforming frames (Norbury et al. (2011)). For instance, the total reaction cross-section of a 500 MeV proton (projectile) impinging on a ^{12}C (target) is the same as the total reaction cross-section of a 500 MeV/u ^{12}C (projectile) on an ^1H (target).

As done for nucleus-nucleus cross-section data (Luoni et al. (2021)), in this work, the experimentally measured data collected in the database are used to benchmark reaction cross-section models employed in radiation transport codes: the Tripathi-Cucinotta-Wilson (Tripathi et al. (1996), Tripathi et al. (1999)), Kox (Kox et al. (1987)), Shen (Shen et al. (1989)), Kox–Shen (Sihver et al. (2014b)), and Hybrid-Kurotama (Sihver et al. (2014a)) models. The Hybrid-Kurotama model is based on the Black Sphere (Kurotama, in Japanese) formula, smoothly connected to the Triapthi-Cucinotta-Wilson parameterization at low energies.

The Kox, Shen, and Tripathi-Cucinotta-Wilson models are implemented in Geant4 (Agostinelli et al. (2003), Allison et al. (2016)), even though none of them is used by default within any of the Geant4 physics lists. Hybrid-Kurotama is the default model for PHITS⁷ (Kox–Shen and Tripathi-Cucinotta-Wilson are options). FLUKA (Battistoni et al. (2015), Hugo et al. (2024)), the NASA HZETRN (Slaba et al. (2020)), and the GSI in-house heavy-ion treatment planning system TRIP98 (Kraemer et al. (2000)) codes use the Tripathi-Cucinotta-Wilson model.

Fig. 3 reports proton-projectile data points collected for ${}^7\text{Li}$, ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{27}\text{Al}$, and ${}^{28}\text{Si}$ targets, in direct and IK. The predictions of the Kox-Shen semi-empirical model are added to guide the reader's eyes through the data.

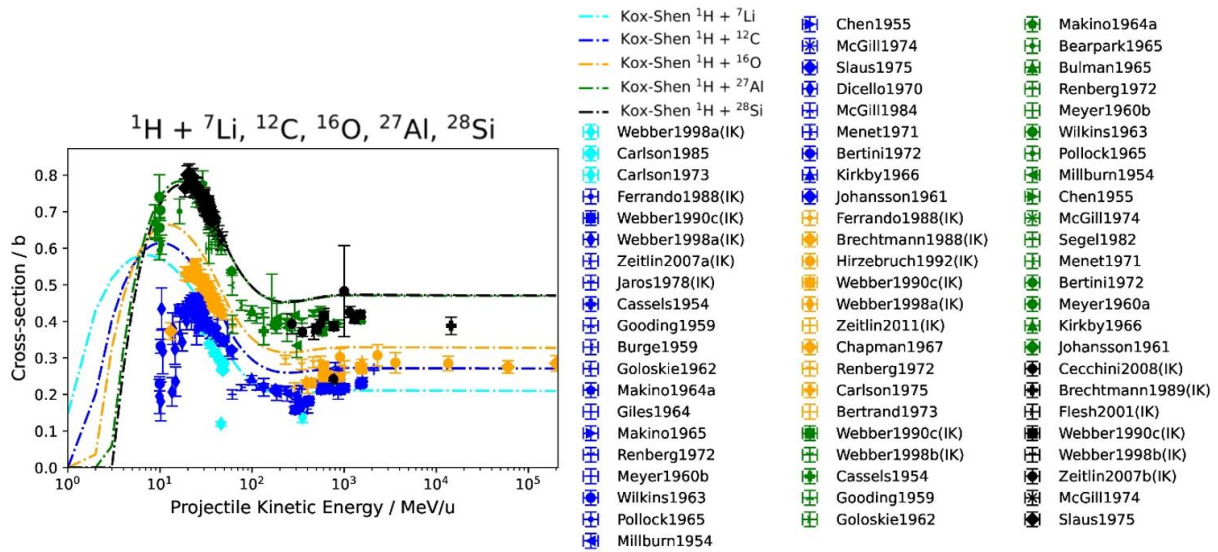


Figure 3: Data collection for proton projectiles on different targets, alongside the predictions of the Kox-Shen semi-empirical model. IK stands for inverse kinematic data. Different colours represent different targets. Both reaction and charge-changing cross-sections are plotted. The references from which the data were collected are reported in the legend.

⁷ <https://phits.jaea.go.jp/manual/manualE-phits.pdf>

In Fig. 4 to 8, proton reaction cross-section data are plotted as a function of the projectile kinetic energy. The predictions of the aforementioned cross-section models are plotted alongside the data. For each set of figures, the subfigure on the left represents the data collection before the addition of proton-projectile data (Luoni et al. (2021)). As a consequence, the experimental data points in the subfigures on the left were all measured in IK. The subfigure on the right also contains the proton-projectile data collected in the scope of this work.

The system $^1\text{H} + ^4\text{He}$ is presented in Fig. 4 because of its importance in IK, as ^4He is a main contributor to dose equivalent in space behind thick shields (Norbury et al. (2020), Luoni et al. (2025)). For $^1\text{H} + ^7\text{Li}$ (Fig. 5), one data point (Carlson et al. (1973)) appears not to agree with the data from the other dataset (Carlson et al. (1985)).

The Tripathi99 model refers to the Tripathi96 model adapted to light nuclei such as protons. The Hybrid-Kurotama model follows the Tripathi99 model until a threshold energy value is reached. Therefore, the two models are superimposed at low energies. For $^1\text{H} + ^4\text{He}$ (Fig. 4), $^1\text{H} + ^7\text{Li}$ (Fig. 5), and $^1\text{H} + ^{12}\text{C}$ (Fig. 6), the Tripathi96 and Tripathi99 differ greatly at low energies. This difference becomes smaller for $^1\text{H} + ^{27}\text{Al}$ (Fig. 7) and $^1\text{H} + ^{56}\text{Fe}$ (Fig. 8). The Hybrid-Kurotama model follows the trend of Tripathi99 at low energies.

For $^1\text{H} + ^4\text{He}$, the Tripathi99 and Hybrid-Kurotama models fit the low-energy data (Sourkes et al. (1976)) well. Data measured by different authors for $^1\text{H} + ^7\text{Li}$ and $^1\text{H} + ^{12}\text{C}$ suggest that the Kox, Shen and Kox-Shen models yield cross-section predictions that are too large at the energies that correspond to the peak of the curve (10 to 30 MeV/u). For higher-Z targets, the discrepancies between models are not as large; due to the scattering of data from the different datasets, no clear conclusion about which models fit the data better can be drawn.

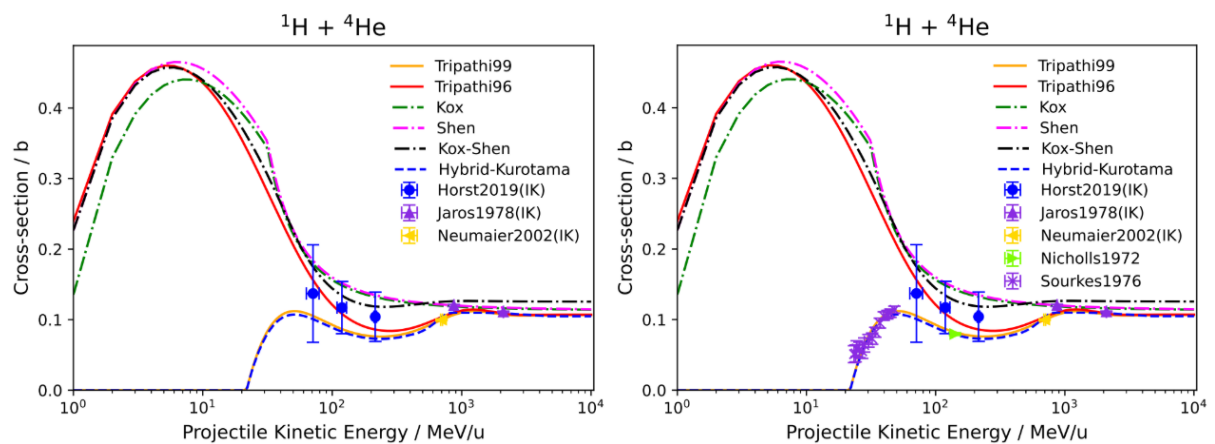


Figure 4: Comparison between models results and cross-section data for proton projectiles on ^4He targets, before (Fig. 4a) and after (Fig. 4b) the addition to the database of proton-projectile data presented in this work. IK stands for inverse kinematic data.

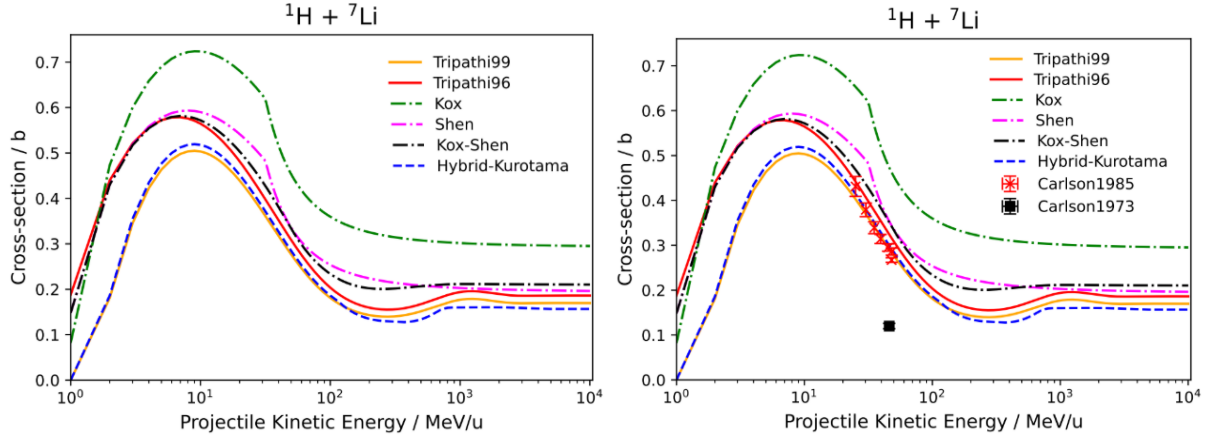


Figure 5: Comparison between models results and cross-section data for proton projectiles on ${}^7\text{Li}$ targets, before (Fig. 5a) and after (Fig. 5b) the addition to the database of proton-projectile data presented in this work. IK stands for inverse kinematic data.

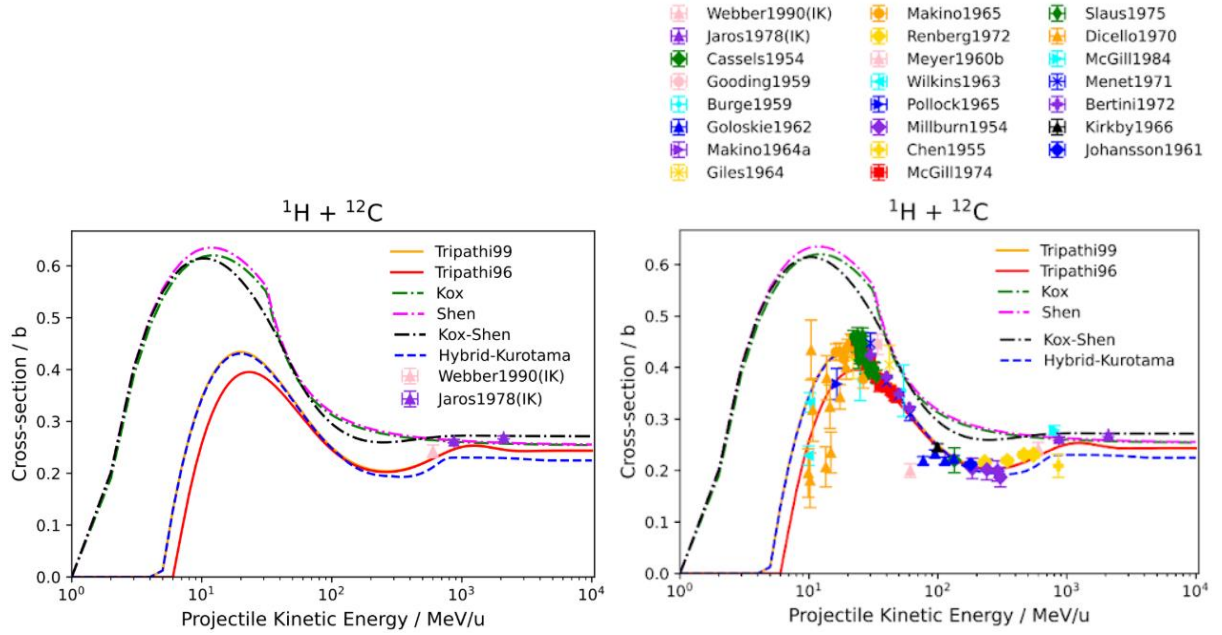


Figure 6: Comparison between models results and cross-section data for proton projectiles on ${}^{12}\text{C}$ targets, before (Fig. 6a) and after (Fig. 6b) the addition to the database of proton-projectile data presented in this work. IK stands for inverse kinematic data.

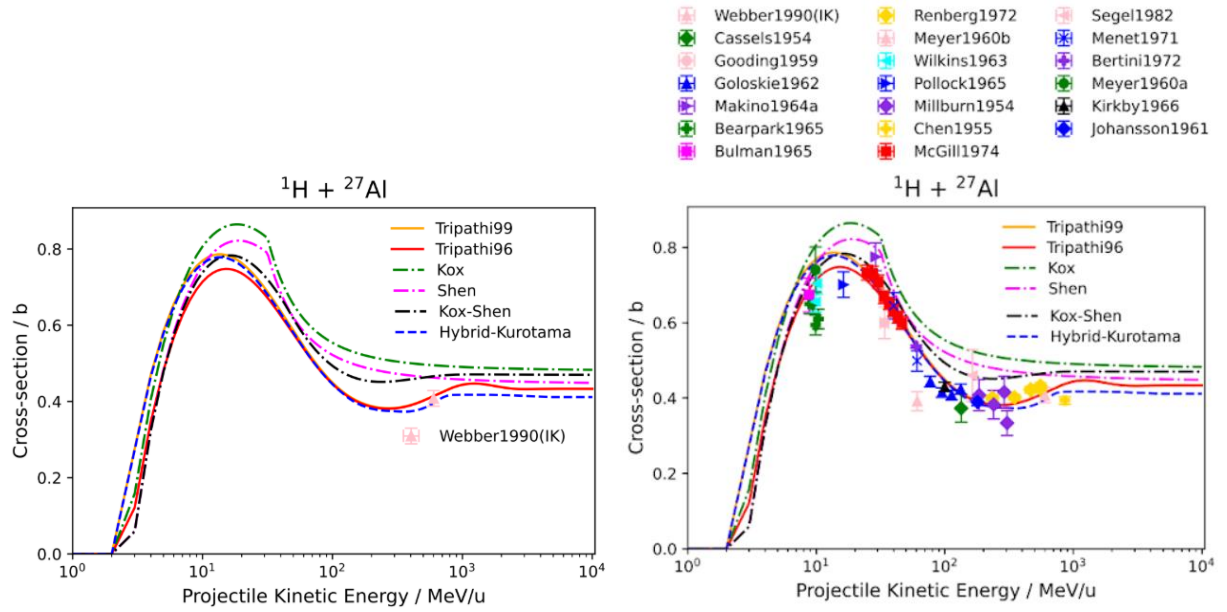


Figure 7: Comparison between models results and cross-section data for proton projectiles on ^{27}Al targets, before (Fig. 7a) and after (Fig. 7b) the addition to the database of proton-projectile data presented in this work. IK stands for inverse kinematic data.

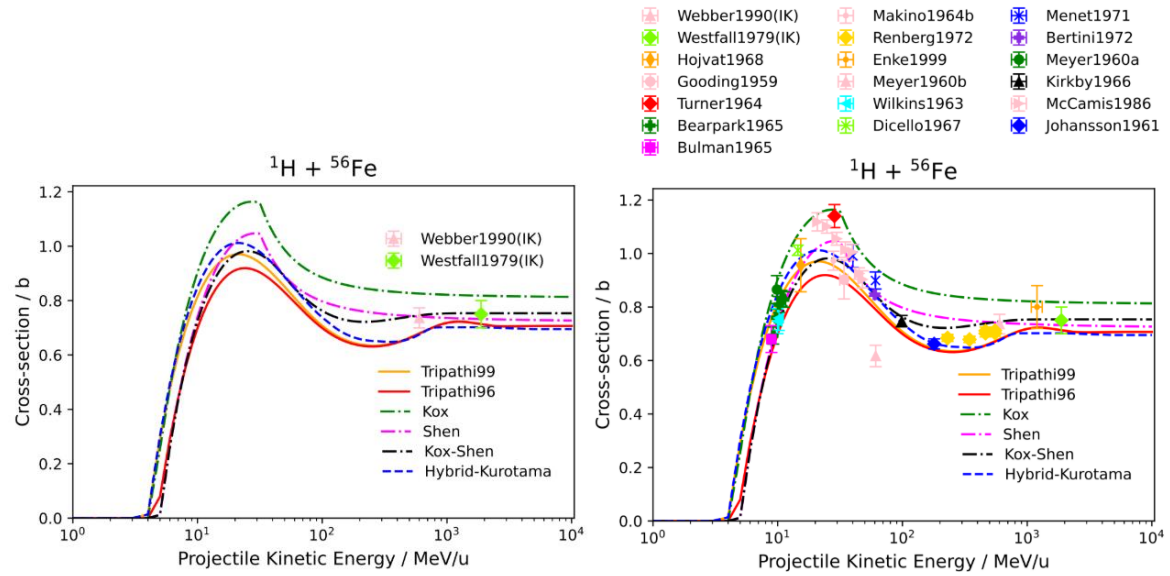


Figure 8: Comparison between models results and cross-section data for proton projectiles on ^{56}Fe targets, before (Fig. 8a) and after (Fig. 8b) the addition to the database of proton-projectile data presented in this work. IK stands for inverse kinematic data.

3. Conclusions

Precise nuclear cross-section measurements are needed for the radiation transport codes used for ion-therapy and space radiation protection applications. Therefore, a nucleus-nucleus reaction cross-section database was generated within a GSI-ESA-NASA collaboration (Luoni et al. (2021)). The collected nucleus-nucleus reaction cross-section data were compared with several nuclear reaction cross-section models implemented in the radiation transport codes used for radiation protection in space and ion-therapy applications, namely the Kox, Shen, Kox-Shen, Tripathi-Cucinotta-Wilson (Tripathi99 for low-Z projectile ions and Tripathi96 for the others), and Hybrid-Kurotama models. As a consequence, the Tripathi-Cucinotta-Wilson model was optimized to better fit all of the collected reaction cross-section data (Luoni et al. (2023)).

Although proton-projectile data were not included in the original database, protons are the main contributors to SEP and GCR fluences in space, accounting for most of the effective dose behind thick shields. Furthermore, protons are the ion beam used in 88% of the cancer-treatment ion-therapy centers worldwide. Proton-projectile data can also be used in inverse kinematics, as ^1H is also an important target for both space radiation and ion-therapy endpoints. Therefore, in this work, the addition of proton-projectile data to the reaction database is presented. The addition of these data facilitates the comparison of the reaction cross-section models to a larger dataset. The Tripathi99 and the Hybrid-Kurotama model, which superimposes with Tripathi99 at low energies, are shown to best reproduce the reaction cross-sections for proton-nucleus collisions.

The database can be found in the free and open-access web application on the GSI official website⁸. The database provides the scientific community with a comprehensive and detailed set of data for benchmarking nuclear reaction models or for other endpoints, including heavy-ion-therapy with innovative (Tessonnier et al. (2023), Sokol et al. (2017), Mizushima et al. (2019)) and radioactive beams (Mohammadi et al. (2019), Boscolo et al. (2021), Horst et al. (2021)), nuclear and accelerator engineering, nuclear physics and astrophysics (Norbury et al. (2012)).

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⁸ <https://www.gsi.de/fragmentation>

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