

Thick-Target Measurements of Light Ion Yields Relevant to Radiation Transport Calculations

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To mom and dad, Francisco and Shawn, and eternally to Nat.

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ABSTRACT

This dissertation presents double differential thick-target yields of secondary light ions (protons, deuterons, tritons, helium-3, and helium-4) produced by interactions of iron, helium, and proton ions with thick aluminum targets. Measurements were taken in March and December 2016 at Brookhaven National Laboratory's NASA Space Radiation Laboratory. During this experiment, ion beams of 400- and 800-MeV/N [megaelectron volt per nucleon] iron, 400- and 800-MeV/N helium, and 400- and 800-MeV [megaelectron volt] protons bombarded aluminum targets of 20, 40, and 60 g/cm² [grams per centimeter squared] thickness. An additional aluminum target of 60 g/cm² thickness was placed 3.5 m downstream to model the observed increase in secondary particle yields in an enclosed space. Surveys of light ions were taken with organic liquid scintillators at 10° [degrees], 30°, 45°, 60°, 80°, and 135° off beam axis. Light ion event contributions were discerned from the total signals in the liquid scintillators by comparing the energy deposited in the liquid scintillator versus time of flight. Combined with a pulse shape discrimination technique, these methods allowed for the identification of Z=1 and Z=2 isotopes. Double differential thick-target yield versus energy spectra were then constructed for the light ion events using the time-of-flight technique.

Protons were measured between 10° and 135° for all projectiles, and deuterons were measured between at least 10° and 45°. Observations of tritons, helium-3, and helium-4 were dependent upon the mass of the projectile and measurement angle. The resulting yield spectra were compared to MCNPX transport model calculations. Additionally, a subset of the results was compared to calculations performed with MCNP's LAQGSM and ISABEL physics models, and the PHITS Monte Carlo code. Light ion yields were best modeled by MCNPX and PHITS for incident iron and helium projectiles, respectively, while light ion yields were well-modeled by both transport codes for proton projectiles. Overall, this experiment is a part of a multi-year project to supplement the existing measurements available for validation and verification of radiation transport codes, which are used to quantify radiation exposure and assess the risk of cancer incurred during long-term, manned space flight missions.

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I. INTRODUCTION

I.1 Dissertation Overview and Outline

Future missions to Mars will be longer than any manned space flight to date, and the radiation exposure the crew would incur on such a trip necessitates a better understanding of radiation transport processes, as well as the radiation field created within shielded environments. Cross section data that are necessary for radiation transport codes to recreate typical fragmentation processes seen in space do not exist. Because of this, an expansive measurement campaign was ordered to measure the fragments created by nuclei in various thick shielding materials. Benchmark data are needed to test the predictive capabilities of radiation transport tools to accurately portray the mixed radiation field that is created when relativistic nuclei fragment in thick shielding. Additionally, the experiment was closely approximated with Monte Carlo transport calculations, and the measured and simulated quantities were compared. The resulting rigorous uncertainty quantification effort will thus enumerate the strengths and weaknesses of the transport models.

This dissertation is arranged as follows: Chapter II contains general information about the space radiation environment and the estimation of dose quantities. Chapter III lists all previous thick-target yield measurements for light ions that are noted in the literature. A brief discussion of the importance of these measurements is also included here. Chapter IV describes the experimental setup and the subsequent analysis techniques that are used to evaluate the light ion measurements. Additionally, the design of the MCNPX and PHITS Monte Carlo simulations are discussed here, along with the differences in their physics model packages. Chapter V starts with a discussion on the existing limitations with the experiment and the analysis techniques. Statistical and systematic uncertainties are also presented in this section, along with uncertainties in the measured energies. Experimental light ion yields are then compared to simulated quantities generated by MCNPX utilizing the CEM03 and LAQGSM03 event generators, while a subset of the results is also compared to calculations performed with an additional MCNP light ion event generator ISABEL, and the PHITS Monte Carlo code. This chapter finishes with a discussion of the general trends

noted in the results. Finally, this dissertation is concluded and future work recommendations are made in Chapter VI.

I.2 Original Contribution

This experiment was designed to measure light ion yields produced by projectile beams that sample the major galactic cosmic ray constituents at kinetic energies representative of the space radiation environment. The double differential thick-target light ion yields produced by 400 MeV/N and 800 MeV/N iron, helium, and proton projectiles incident on 20, 40, and 60 g/cm²-thick aluminum targets have never been measured before, and the placement of a second, 60 g/cm² aluminum target in the beamline has not been replicated. Additionally, original simulations were designed by the author using different physics models and transport codes for comparison to the measured yields. These comparisons will help further the discussion on the disparities that exist between different Monte Carlo calculations for light ion production and transport in thick-targets, which will ultimately help improve the design of the physics models and their subsequent outputs. Overall, the resulting 258 unique spectra will supplement the existing measurements available for validation and verification of radiation transport codes. Ultimately, these transport codes are used to quantify the radiation doses due to chronic exposures incurred during long-term manned space flight missions, and assess the overall risk of exposure-induced death.

I.3 Dissertation Goals

Overall, the goal of this dissertation is to highlight the differences in the light ion formation and transport modalities for a series of Monte Carlo physics models, and then compare the simulated yields to experimentally-measured double differential thick-target yields. Measurements presented in this work will be incorporated into a database for use by NASA Langley Research Center to validate transport code outputs for thick target-produced light ion yields. Specific goals for this dissertation include:

1. Calculate never before measured double differential thick-target light ion (proton, deuteron, triton, helium-3, helium-4) yields for eighteen projectile-target systems at up to six angular locations.
2. Calculate statistical, systematic, and energy uncertainties for measured yields.
3. Model the experiment in MCNPX, utilizing an event-by-event particle tracking technique to eliminate light ions that originate from target room locations other than the upstream target. Compare the simulation and measurement results.
4. Compare a subset of the measurement data to simulated light ion yields generated with MCNP's LAQGSM and ISABEL physics model event generators, as well with the PHITS Monte Carlo code.

II. GENERAL INFORMATION

II.1 Space Environment

The space radiation environment poses difficulties for extended human spaceflight missions beyond the extent of the Earth's own magnetic field. Galactic cosmic rays (GCR) are highly energetic particles consisting of 98% atomic nuclei stripped of their electrons with the remaining 2% composed of unbound electrons and positrons. Of the baryonic matter, 87% are hydrogen nuclei, 12% are helium nuclei, and 1% are divided between the remaining periodic elements, with nickel being the heaviest significant constituent [1]. The energy spectra of various GCR component nuclei measured at Earth are presented in Figure 1. This illustrates the peak in flux of the various GCR components between 10^2 and 10^3 MeV/nucleon (MeV/N). The relative abundance of the significant constituents as a function of charge number z at three energies can be seen in Figure 2. These values are normalized to the abundance of silicon and multiplied by a factor of 1000. Hydrogen contributions are an order of magnitude greater than helium contributions, which are subsequently an order of magnitude greater than the relative abundance of any of the heavier nuclei. Iron is the most abundant of the heavy nuclei. As noted in [2], the kinetic energy spectrum of iron is higher in magnitude at energies above 1 GeV/N when compared to the energy spectra of light nuclei in the same energy range. This is noted in the abundances shown in Figure 2, as the ratio of the iron to helium abundances is greater at 5 GeV (green) than at 0.2 GeV (red) on the kinetic energy spectra.

GCR nuclei traveling at highly relativistic kinetic energies penetrate the structural materials of spacecraft and continuously lose kinetic energy via electronic interactions in the medium. The average energy lost by per unit path length traveled by charged particles is known as linear energy transfer (LET) [2]. Additionally, nuclear interactions such as fragmentation may also occur when GCR nuclei interact in a shielding material, which may lead to the expulsion of nucleons and the formation of light ions. During a fragmentation reaction, the incident nuclei are broken up into multiple secondary nucleons and nuclei with varying masses and energies. The decreased mass of fragmented projectiles causes them to have an increased range of penetration relative to the original projectile. Additionally, the light ion components of the primary GCR, hydrogen and helium

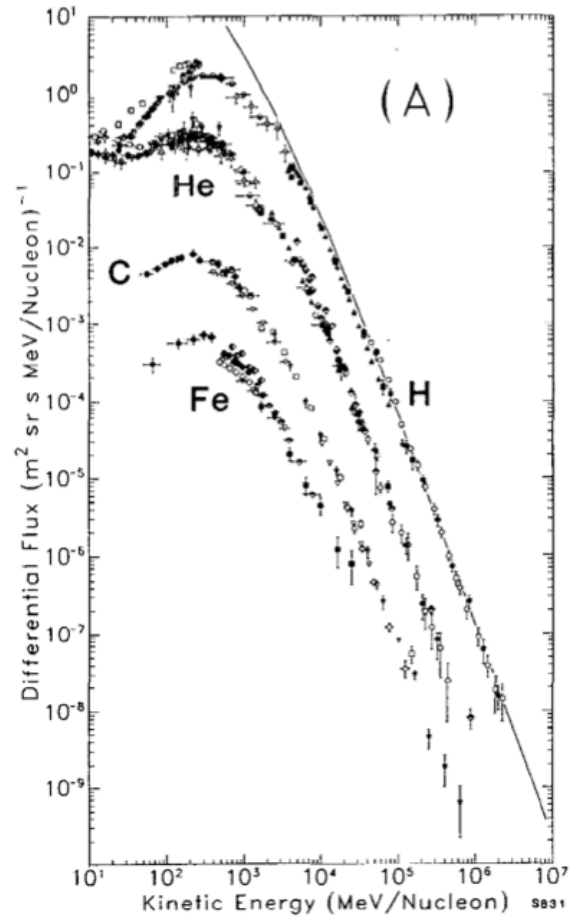


Figure 1. Elemental spectra of the GCR measured near Earth [1].

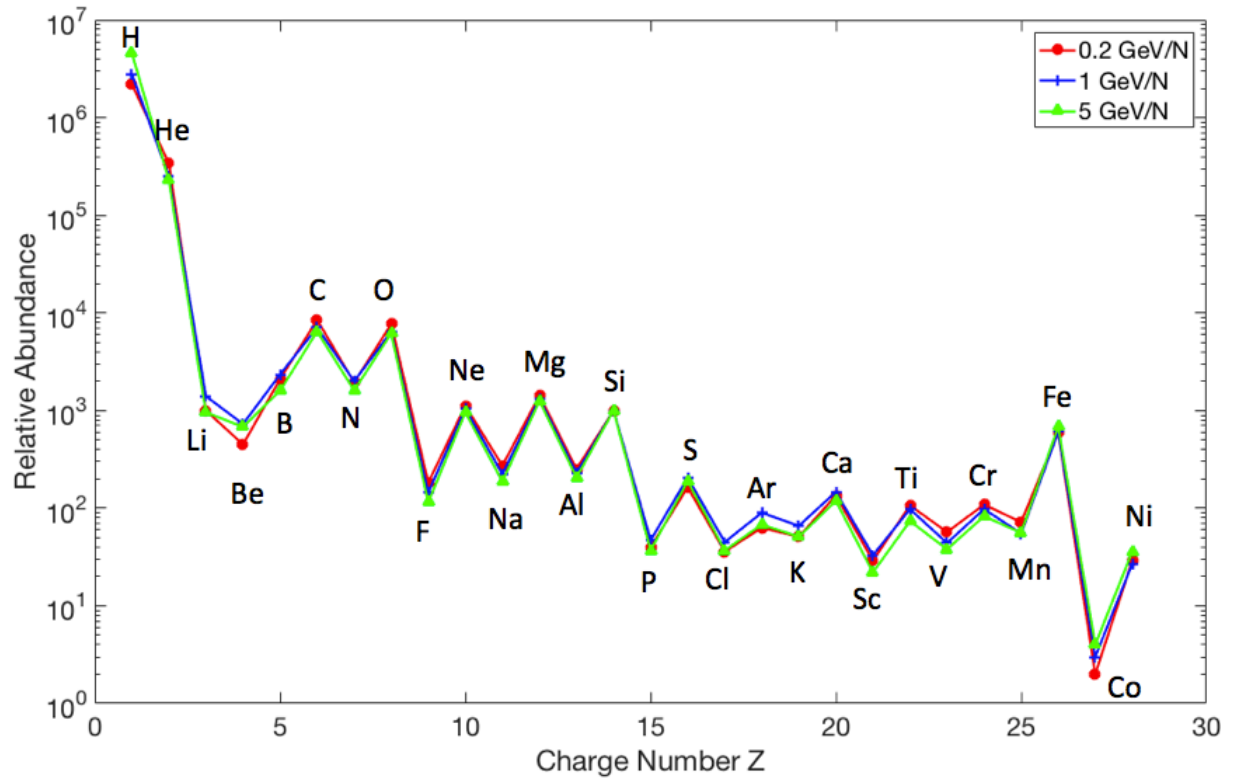


Figure 2. Relative abundances of nuclei in GCR, normalized to silicon and multiplied by 1000, at three kinetic energies points of the spectrum. Values from [2].

isotopes, participate in forward-focused knock-out and pickup reactions. These reactions result in additional secondary light ions with high kinetic energies and large depths of penetration, which have significant contributions to energy deposition behind thick shields [3]. In all, the propagation of GCR through spacecraft incite a cascade of nuclear interactions in shielding materials.

The secondary radiation field created by a GCR-target interaction must be accurately characterized to assess the safety of crewed spaceflight missions, and to protect any electronic components from radiation damage. The resulting radiation field behind shielding will deposit energy to flight equipment or tissue in the form of absorbed dose D measured in Gray (J/kg). There are various particle types represented in the secondary radiation field, each with differing characteristics and mechanisms of energy deposition. This is generally referred to as the radiation quality. The most appropriate quantity used for the estimation of health risks posed by these radiation fields is the dose equivalent H in Sieverts (Sv). This is calculated by multiplying the absorbed dose by a quality factor QF . Commonly used QF s for spaceflight mission planning have been determined [4] as a function of the incident radiation's LET in water. Different formulations of quality factors have also been developed to include greater sensitivity to track structure as a function of charge number z and velocity β [5], [6], but are not considered in the subsequently discussed studies.

A mission to Mars will prove difficult from the standpoint of dose and possible health risks. Measurements by Zeitlin *et al.* [7] with the Radiation Assessment Detector (RAD) aboard the Mars Science Laboratory (MSL) spacecraft indicate that the dose equivalent from a nominal 360-day round-trip journey would be 662 mSv. The NASA formulation of risk [5] puts in place career exposure limits that will not increase the risk of exposure-induced death (REID) beyond 3% assessed at a 95% confidence interval. The round-trip exposure noted above either surpasses or is a significant portion of the career dose limit for typical astronaut demographics [7]. With these findings in mind, an effort must be made to reduce the uncertainties related to chronic low doses incurred during long duration missions behind shielding by gaining further insight into the transport processes of GCR.

II.2 Radiation Field in Enclosed Environment

Both deterministic and Monte Carlo radiation transport codes are used to model the resulting secondary radiation field behind shielding materials. Both transport code methodologies need double-differential cross section data to accurately calculate the production of light ions via the nuclear reactions between GCR constituent nuclei and common spacecraft structural materials. Measured data for these reactions in the kinetic energy regions of importance do not exist [8]. Nuclear physics models are used to approximate the secondary particle production by making systematic assumptions about the matter and momentum distributions of the participating nuclei, the reaction dynamics, and the mechanisms of decay of any excited nuclei. Monte Carlo codes typically utilize intra-nuclear cascade models to simulate the direct nuclear reaction and other assumptions to handle the subsequent de-excitation of nuclei. Further detail of the physics models used by the Monte Carlo codes directly utilized in this dissertation can be found in Section IV.6.

Slaba *et al.* [9] conducted a study to benchmark HZETRN against Monte Carlo codes commonly used in the radiation protection community. This study utilized these simulation tools to calculate dose and dose equivalent behind shielding of various thicknesses. The geometry employed for this study involved a pair of semi-infinite aluminum or polyethylene shields of matching material and longitudinal thickness, enclosing a thin liquid water layer that was used to score the fluence of secondary particles and the dose in the scoring region. A full GCR reference spectrum, representative of solar minimum conditions, was produced by the Badhwar O'Neil 2010 model (BON2010) and was set incident on the exterior face of one target.

A unique result was found when comparing the integral neutron and light ion dose equivalent contributions calculated by each transport code, as presented in Figure 3. Three variations of HZETRN results presented represent one (N=1), two (N=2), and three (N=34) spatial dimension versions of the code. When plotting dose equivalent as a function of shield thickness, a local minimum was found at 20 g/cm² of target slab thickness by each transport code for simulations using aluminum targets, with the dose equivalent increasing as the shielding thickness increased. The majority of this rise in dose equivalent was due to contributions from proton secondaries. The relative contribution of protons to the estimated dose equivalent was greater than 50% for shields greater than ~35 g/cm² thickness. A significant portion of this increasing proton contribution with

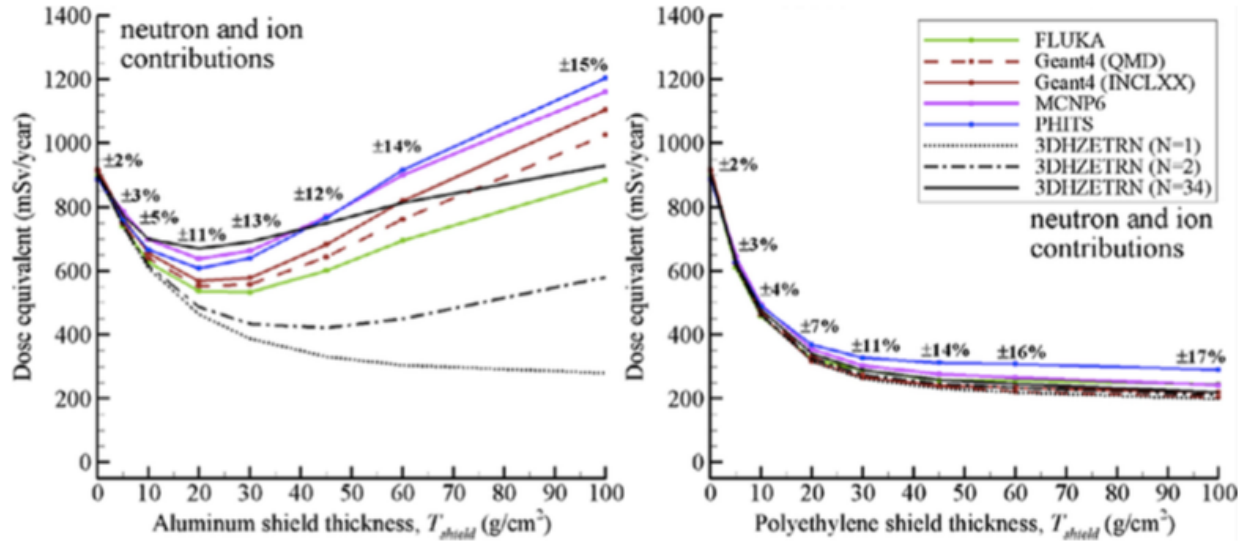


Figure 3. Neutron and light ion contributions to dose equivalent measured between two semi-infinite slabs of aluminum (left) and polyethylene (right), when exposed to the BON2010 solar minimum GCR environment [9].

thicker shields is due to neutron-hydrogen recoils. Other hydrogen isotope and helium light ions contributed 10 to 20% of the relative total dose equivalent for large shield thicknesses [9].

Also of note is the variance in the dose equivalent results between the different transport codes, denoted in Figure 3 with the numbers along the plotted lines. These numbers quantify the variation between the three dimensional (N=34) HZETRN result and the Monte Carlo results by dividing half the absolute range between maximum and minimum results at a given thickness by the average of this range. These differences were driven by the uncertainty in light ion production, although the variation between different transport models does not increase significantly with shield thickness beyond the minimum, as seen with heavy ions [9].

II.3 Measurement Plan

The identification of a local minimum in dose equivalent as a function of shield thickness for aluminum targets prompted the Thick GCR Shielding Project to be commissioned by NASA. This series of accelerator-based measurements performed at the NASA Space Radiation Laboratory (NSRL) at Brookhaven National Laboratory was designed to experimentally validate the simulated contributions of neutrons and light ions to the increased dose calculated in between thick shields. The projectile-target systems studied in this campaign are presented in Table 1.

Measurements were taken in three (marked in color on Table 1) increments: 100 hours in March 2016 (blue), 200 hours in December 2016 (orange), and 200 hours in November 2017 (gray). The experiments sought to replicate the enclosed geometry modeled by Slaba *et al.* [9] by placing rectangular aluminum, polyethylene (CH₂), and dual (Al/CH₂) stacked-slab targets 3.5 meters apart. The downstream target material matched the upstream target material in the single-material target configurations, while the dual-material upstream targets utilized a downstream polyethylene target. Light ions and neutrons were measured at six liquid scintillator positions using time-of-flight techniques. Each single-material target configuration shown in Table 1 utilized three thicknesses of upstream target (20, 40, and 60 g/cm²), while the dual-material targets only tested two upstream target thicknesses (10 g/cm² of aluminum in front of either 10 or 50 g/cm² CH₂). In all, 120 different projectile-target configurations were measured.

The double differential yields of light ions being presented in this dissertation resulted from the six projectile-target combinations underlined in Table 1: 400 and 800 MeV/N projectiles of iron, helium and hydrogen on aluminum targets. The five March 2016 reactions were measured first because they represented the heaviest and lightest ions of the major GCR constituents, and would be the most effective reactions to initialize and optimize the data acquisition system for the detection of light ions and neutrons. Additionally, the 800 MeV/N helium data set was added to this dissertation to complement the 400 MeV/N helium dataset.

Table 1. Projectile-target systems studied as part of Thick GCR Shielding project.

Beam Species/ (MeV/N)	Proton			Helium			Carbon			Silicon			Iron		
400	<u>Al</u>	CH ₂	Al/ CH ₂	<u>Al</u>	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂	<u>Al</u>	CH ₂	Al/ CH ₂
800	<u>Al</u>	CH ₂	Al/ CH ₂	<u>Al</u>	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂	<u>Al</u>	CH ₂	Al/ CH ₂
1500 (2500 for H)	Al	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂	Al	CH ₂	Al/ CH ₂

III. LITERATURE REVIEW

III.1 Existing Double Differential Thick-Target Light Ion Yield Measurements

Experimentally measured double differential thick-target light ion yields found in literature were measured at various hadron therapy facilities to characterize the fragmentation of the projectile beams for use in radiotherapy, or to quantify the source term of the secondary radiation field for facility shielding purposes. A summary of these works can be found in Table 2. The measurements primarily focused on shielding considerations were those performed by Kurosawa, *et al.* [10]. The experiment performed at the Heavy Ion Medical Accelerator (HIMAC) facility in Chiba, Japan bombarded 100 MeV/N helium projectiles on carbon (8.9 g/cm²), aluminum (10.8 g/cm²), copper (13.4 g/cm²), and lead (17 g/cm²) targets. Each target was sufficiently thick to stop the incident projectile. The Kurosawa experiment utilized detection and acquisition systems that are generally replicated by the other works in Table 2, as well as by the experiment analyzed in this dissertation. Measurements of protons (p), deuterons (d), and tritons (t) were taken at 0°, 7.5°, 15°, 30°, 60°, and 90° utilizing organic liquid scintillators; the target was rotated 45° to minimize the attenuation of secondary fragments for the measurements between 30° and 90°.

Double differential yield measurements of light ions were additionally performed at the GSI Helmholtz Centre for Heavy Ion Research (GSI) in Darmstadt, Germany to characterize the contributions of light ions to radiotherapy treatments. The work published by Gunzert-Marx *et al.* [11] studied the secondary light ions produced by 200 MeV/N carbon projectiles incident on a 12.8 g/cm² water target, which was thick enough to stop the incident projectile. Proton, deuteron, and triton yields were measured at 0°, 10°, 20°, and 30°, and helium-3 and helium-4 fragments were also measured at 0°, 5°, and 10°. These light ions were measured using barium fluoride (BaF₂) detectors as the primary calorimeter. Both the works of Kurosawa and Gunzert-Marx utilized pulse shape discrimination techniques to provide elemental separation of the detection events of light ions. Additionally, both works provide comparisons of the measured energy spectra to Monte Carlo simulations: the LAHET Code System (LCS) [12] and PHITS [13], respectively. The rest of the works presented in Table 2 do not provide comparisons of the presented energy spectra to transport code calculations.

Table 2. Published double differential thick-target light ion yield measurements.

Facility	Lead Author	Projectile	Energy (MeV/N)	Target	Ions Measured
HIMAC	Kurosawa	He-4	100	C, Al, Cu, Pb	p, d, t
GSI	Gunzert- Marx	C-12	200	H ₂ O	p, d, t, He-3, He-4
GSI	Haettner	C-12	400	H ₂ O	H, He, Li, Be, B (no isotope I.D.)
GANIL	Braunn	C-12	95	PMMA	H, He, Li, Be, B, C
HIT	Rovituso	He-4	120, 200	H ₂ O	p, d, t, He-3, He-4
HIT	Marafini	He-4	102, 125, 145	PMMA	p, d, t

Double differential elemental yields have also been measured to assess the effect of fragmentation processes on the depth-dose curves used in radiotherapy treatment planning. Double differential energy spectra for elemental hydrogen through boron were measured in the work published by Haettner *et al.* [14]. 400 MeV/N carbon beams were incident on water targets with thicknesses of 5.9, 15.9, 27.9, and 34.7 g/cm², and the latter two thicknesses were able to stop the incident beam. Measurements of hydrogen and helium fragments were measured at 0°, 2°, 4°, and 6° with a BaF₂ detector. Additionally, double differential elemental yields of hydrogen through carbon were measured at the Grand Accélérateur National d'Ions Lourds (GANIL) in Caen, France by Braunn, *et al.* [15] from reactions of 95 MeV/N carbon on PMMA thicknesses of 0.6 to 3 g/cm², but energy spectra were only published for a single detection angle of 7° using Cesium Iodide (CsI) and bismuth germanate (BGO) detector in coincidence. Time-of-flight analysis techniques were not used in either of these experiments, unlike the other works in Table 2, and the work presented in this dissertation.

Measurements of light ions have been performed recently at the Heidelberg Ion-Beam Therapy Center (HIT) in Heidelberg, Germany to characterize the dose characteristics of helium beams for the use in radiotherapy. The work by Rovituso *et al.* [16] presents the light ion yields of hydrogen and helium isotopes from 0° to 6° using BaF₂ detectors, for 120 and 200 MeV/N helium projectiles incident on water targets that were 4.3 and 13.9 g/cm² thick. These target thicknesses were selected to degrade the range of the incident projectile in half. Marafini *et al.* [17] provided additional measurements of hydrogen isotope light ions resulting from 102, 125, and 145 MeV/N helium projectiles on poly-methyl methacrylate (PMMA) of sufficient thickness to stop each incident projectile. Hydrogen isotope light ions were measured at angles between 0° and 30° with a BGO detector.

The measurements presented in these works were not focused on approximating GCR-like interactions with thick targets. Measurements of double differential light ion yields for projectiles at 800 MeV/N have not been published, and measurements with 400 MeV/N projectiles are minimal. Light ion yields for iron projectiles are not found in literature, through light ion yields produced by helium projectiles are noted at lower than desired incident energies. Additionally, light ion yields from aluminum targets with large thicknesses (20, 40, and 60 g/cm²), relative to

the target thicknesses used in prior measurements, have not been published, but will be presented in this work. The targets utilized in the measurements for this dissertation were sufficient to stop the iron projectiles, but not the helium and proton projectiles. Moreover, no experiment to date has utilized a dual-target configuration to approximate enclosed spacecraft conditions. Finally, comparisons between measured light ion yield spectra and multiple transport models will also be presented in this dissertation.

IV. EXPERIMENTAL SETUP AND ANALYSIS TECHNIQUES

IV.1 Experimental Layout and Design

IV.1.1 Overview of NSRL Facility

The March and December 2016 experiments were conducted at Brookhaven National Laboratory's NASA Space Radiation Laboratory (NSRL). The NSRL accelerator facility is devoted to providing charged particle beams for space radiation research purposes [18]. The main portion of the target room has a cross-sectional area of $6.1 \times 6.1 \text{ m}^2$, with a floor-to-ceiling height of 3.05 m. The beam axis is 1.22 m above the floor and a pair of 2.5 cm diameter steel rails are placed 0.87 m above the floor. Targets and other equipment are attached to this rail system. Light ions (protons, deuterons, tritons, helium-3, and helium-4) produced by 400 and 800 MeV/N iron, helium, and proton interactions on 20, 40, and 60 g/cm²-thick aluminum targets were measured at 10°, 30°, 45°, 60°, 80°, and 135° off beam axis using liquid scintillator arrays. A second, 60 g/cm²-thick aluminum target was also added 3.5 m downstream. A simplified schematic of the NSRL target room with the radiation detectors and target location information is presented in Figure 4, and an image of the experimental setup is shown in Figure 5.

Two ion sources are currently used at the NSRL. The Tandem van de Graff was the ion source used to deliver all beam species up to gold from NSRL's inception in 2003 until 2010. It is still used today to supply protons to the NSRL facility, if necessary. The Electron Beam Ion Source (EBIS) was introduced to provide a more robust ion source that can quickly switch between different ion sources to more effectively serve both the NSRL and the Relativistic Heavy Ion Collider (RHIC). EBIS can further provide noble gas ions and elements up to uranium. Particles extracted from EBIS are further accelerated by a radiofrequency quadrupole accelerator to 30 MeV, and then by a linear accelerator up to 200 MeV [19]. Up to the points described, both ion sources are then fed into the Booster accelerator. The Booster is an alternating gradient synchrotron that can then deliver energies up to 1500 MeV/N for iron and helium, or up to 2500 MeV for protons to the NSRL target room. Each beam spill may last between 300 ms and 2 s, and spills may be supplied every 4 to 6 s [18]. The spill length and cycle can vary depending on if RHIC is operating at the same time as NSRL. While the accelerator can deliver beams with cross sections

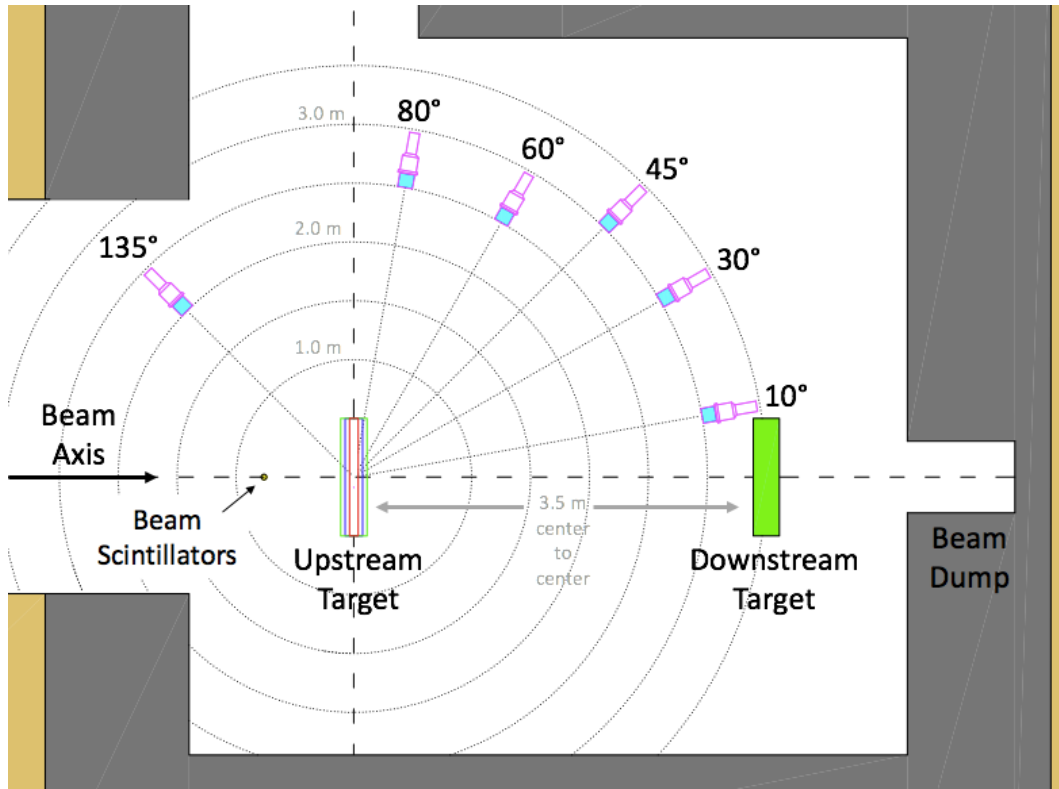


Figure 4. Generalized NSRL target room depicting the thick-target measurement equipment, to-scale. 20, 40, and 60 g/cm² upstream aluminum target widths depicted by red, blue, and green lines, respectively.

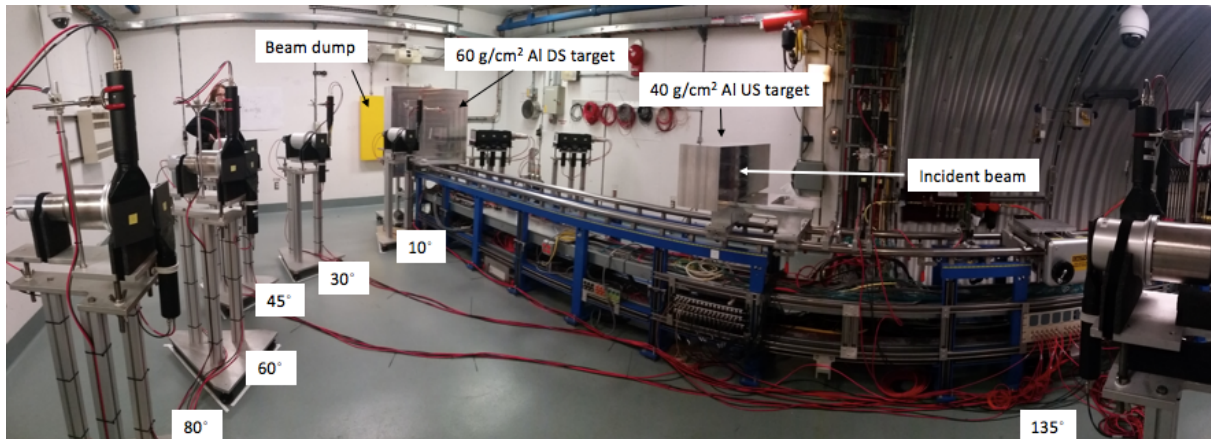


Figure 5. Panorama of NSRL target room.

up to 60 by 60 cm², beams with Gaussian-distributed profiles of standard deviation less than 6 cm were utilized for this experiment.

IV.1.2 Projectile Beam Information

400 and 800 MeV/N iron, 400 and 800 MeV/N helium, and 400 and 800 MeV proton projectiles were selected for the March and December 2016 experiments. Projectiles entered the target room 1.22 m above the floor after passing through the 381 μ m-thick aluminum beam exit window. Gaussian distributions fit the transverse profile of the beams, with standard deviations ranging from approximately 2.5 cm to 6 cm for the 800 MeV/N helium and 400 MeV proton projectiles, respectively. Approximately 1,000 to 2,000 ions were delivered per spill, varying with the beam species and energies.

IV.1.3 Target Information

The upstream (US) targets were constructed of 10 g/cm² (3.7 cm) width slabs of aluminum, 30 cm tall by 100 cm long. Three different total US target thicknesses were used: 20, 40, and 60 g/cm², indicated by the red, blue, and green lines in Figure 4, respectively. US targets were placed on a special stand that rested on the rail system, which facilitates the switching of target thicknesses while maintaining a consistent origin for the experiment coordinate system. A second downstream (DS) aluminum target was added to approximate an enclosed space as studied by Slaba *et al.* [9], which is represented by the green rectangle in Figure 4. This target was formed by two, 30 g/cm² aluminum blocks (60 g/cm² total thickness) with a cross sectional area of 100 by 100 cm². The downstream target was held in place by a robust table placed at the end of the rail system. The targets were placed 3.5 m apart, as measured from each target's center.

It should be noted that the incident projectiles punched through the majority of the US aluminum targets. The amount of energy lost by the incident projectiles in the US target was calculated using a MATLAB program described in Section IV.4.2. The resulting energies upon exiting the targets are summarized in Table 3.

Table 3. Projectile energies upon exiting the US aluminum targets (MeV/N).

Projectile	Kinetic Energy (MeV/N)	US Target Thickness (g/cm ²)		
		20	40	60
Fe	400	Stops in 8.9 g/cm ²		
	800	284	Stops in 25.1 g/cm ²	
He	400	351	298	239
	800	763	725	687
H	400	351	298	238
	800	763	725	687

IV.1.4 Detector Information

IV.1.4.1 Beam Scintillators

The pair of beam scintillators is represented by the small yellow circle in Figure 4. These scintillators are placed upstream from the US aluminum target and are used to verify the suitability of the incident particles to start the acquisition system, as discussed later. The beam scintillator at the most upstream position is struck by the projectile beam first, and is denoted as “Start 1” or “S1,” while the second beam scintillator is denoted as “Start 2” or “S2.” S1 and S2 have the same thickness (0.2 cm), though the cross-sectional area of S1 is smaller than S2. A summary of the model, material composition, voltage settings, and physical dimensions for the beam scintillators are contained in Table 4.

For the iron projectiles, two EJ-228 plastic paddles were placed 78.45 cm upstream from the US aluminum target and were spaced by 7.9 cm. With the proton and helium projectiles, the EJ-228 plastic paddles triggered on both incident projectile particles and ambient gamma rays, which lead to issues with the data acquisition. To ensure the beam scintillators only triggered on incident projectiles, a different set of EJ-228 detectors were used (Figure 6). These EJ-228 plastic scintillators were smaller in size and were housed in an aluminum tube with the beam entry hole covered by Tedlar film. This minimally impeded the beam and reduced the leakage of light. The scintillators inside the tube were spaced by 3.0 cm and the tube was placed 76 cm upstream from the US aluminum target, measured from US target center and midpoint between scintillators.

Table 4. Summary of detector properties and settings.

Detector (quantity)	Detector Type (material composition and density)	Voltage Setting	Physical Dimensions
Beam scintillator (S1 and S2)	EJ-228	400, 800 MeV/N Fe	Fe projectiles
	- PVT, anthracene-doped	- 1500 and 1500 V	- 4 x 4 x 0.2 cm ³ (S1)
	- 1.023 g/cm ³	400 MeV/N He	- 5 x 5 x 0.2 cm ³ (S2)
		- 1700 and 1450 V	He and H projectiles
		800 MeV/N He	- 1 x 1 x 0.2 cm ³ (S1)
		- 2000 V	- 1.4 x 1.4 x 0.2 cm ³ (S2)
		400, 800 MeV H	
		- 2040 and 1700 V	
Plastic veto detector (x12)	EJ-204	2000 V	12.7 x 12.7 x 0.635 cm ³
	- PVT		
	- 1.023 g/cm ³		
Organic liquid scintillator (x6)	EJ-301 (10°, 30°, 45°)	10°	12.7 cm diameter
	- Xylene, naphthalene, POPOP, and activators	- 1500 V	12.7 cm depth
	- 0.874 g/cm ³	30° and 45°	
		- 1400 V	
	EJ-309 (60°, 80°, 135°)	60° and 80°	
	- 0.959 g/cm ³	- 1700 V	
		135°	
		- 1900 V	

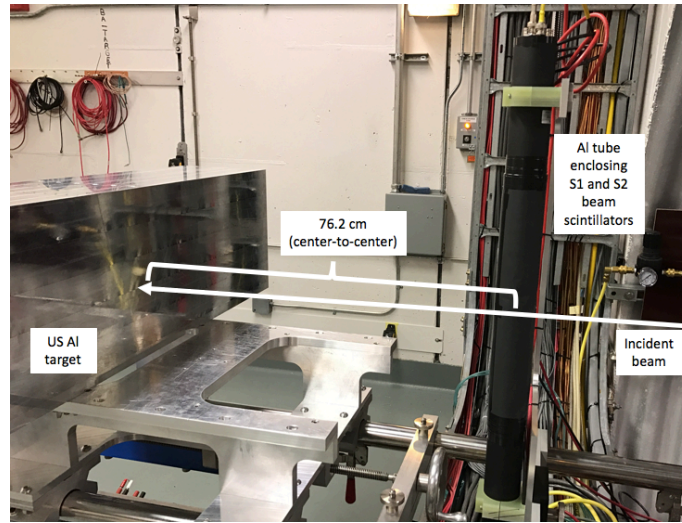


Figure 6. Beam scintillator for helium and proton projectiles.

IV.1.4.2 Organic Liquid Scintillator Arrays

Six cylindrical organic liquid scintillators (OLS) were used to detect light ions and are depicted in magenta in Figure 4, with properties listed in Table 4. These were placed at a maximum distance of 3.0 m (10° , 30° , and 45°) from target center, with certain detectors placed at 2.5 (60° and 80°) or 2.0 m (135°) away from the US target to increase the geometric efficiency to compensate the reduction in particle yields at wider angles from beam axis. The active volumes of these detectors, depicted in light blue, have a radius of 12.7 cm and a depth of 12.7 cm, and are covered by 0.15 cm-thick aluminum casing. Flight paths from the center of the US aluminum target to the front face of the active volume of the OLS are shown in Table 5. The three forward-most detectors at 10° , 30° , and 45° were xylene-based EJ-301 liquid scintillators, with a density of 0.874 g/cm^3 . The other three detectors at 60° , 80° , and 135° were similar EJ-309 liquid scintillators, with a density of 0.959 g/cm^3 . Each OLS was placed on a custom detector stand to consistently align each with the plane of the beam axis.

Each stand was also outfitted with two, thin EJ-204 plastic scintillators, which were 0.635 cm thick with a cross-sectional area of $12.7 \text{ by } 12.7 \text{ cm}^2$. One was placed directly in front of the OLS face, while the other was oriented parallel to the beam axis to gauge the effects of charged particle production or scattering in the air column along the beam axis. These “veto” detectors were used to separate neutral and charged particle events, based on their thinness and particle interaction probabilities [20]. Both the OLS and veto detectors are shown in Figure 7.

IV.1.5 Shadow Bars

Finally, the background radiation environment was characterized by employing iron shadow bars with a 12.7 cm radius. The shadow bar for the 10° to 45° OLS was 182 cm long, while the shadow bar for the 60° to 135° OLS was 91 cm long. The bars obscured the active volume of the OLS from the US target to characterize radiation originating from sources other than the US aluminum target. This is of specific importance for the neutral particle measurements. Only un-shadowed runs (no shadow bars) were considered during the charged particle analysis. An example of a shadow bar run is shown in Figure 8, with the shadow bars blocking the 45° and 135° OLS arrays.

Table 5. Flight paths from the center of the US target to the front face of the OLS active volume.

Detector	Flight Paths (cm)	
	March 2016	December 2016
10°	300.99	301.72
30°	301.59	301.28
45°	301.52	301.33
60°	251.69	251.31
80°	251.32	251.35
135°	201.18	201.93

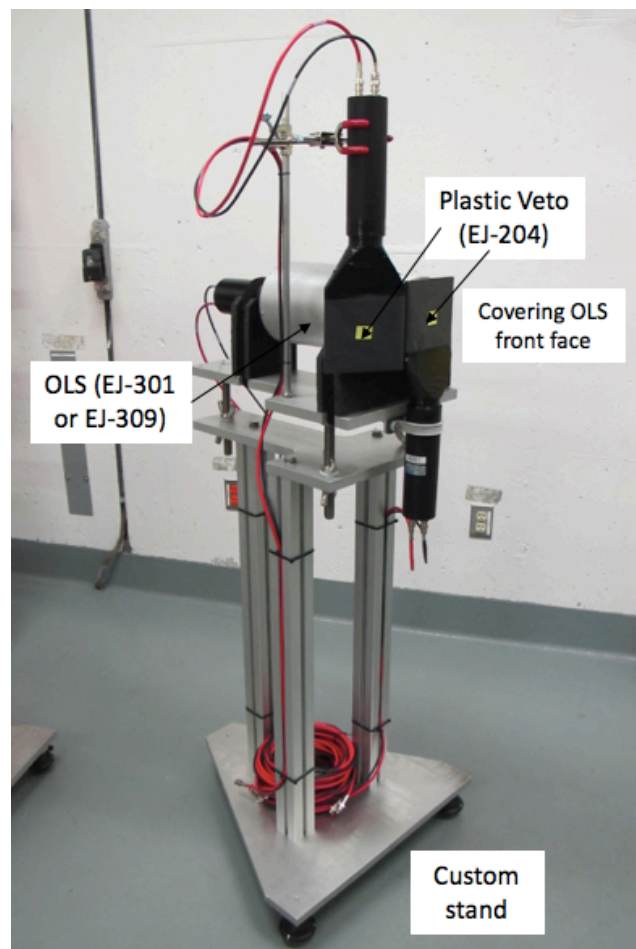


Figure 7. OLS array with custom stand.

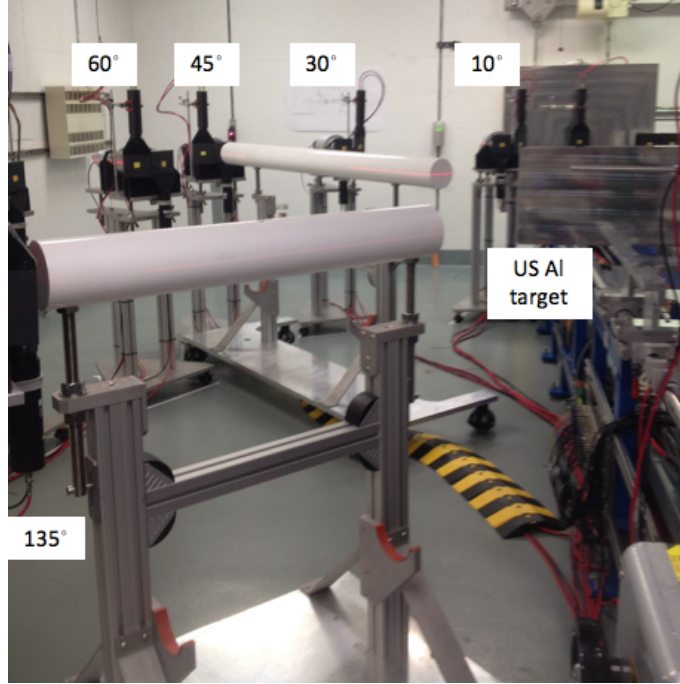
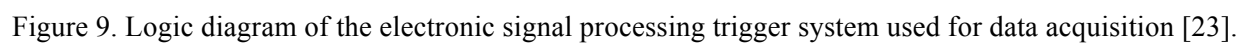


Figure 8. Iron shadow bars blocking the 45° and 135° OLS arrays.

IV.2 Data Acquisition Apparatus

A diagram detailing the signal processing system for this experiment is presented in Figure 9, with logic equipment presented in Table 12 (Appendix I). Event-by-event timing and charge deposition data were acquired using time-to-digital converter (TDC) and charge-to-digital converter (QDC) units, respectively. The CC-USB CAMAC Crate controller passed the acquired data to the acquisition laptop, where the data was monitored using Michigan State University's National Superconducting Cyclotron Laboratory's SpecTcl analysis software [21]. Later, the data files were converted and analyzed using the ROOT Data Analysis Framework [22].

A reverse timing logic setup is utilized in this experiment to ensure that the data acquisition system is halted after a preset time if no event registers in a trigger detector. Reverse timing means that time increases from right to left in the TDC timing spectra, so faster timing signals have higher TDC channel values. The acquisition system is triggered when a valid event is detected in an OLS or a sodium iodide array's veto paddles (labeled as CS in Figure 9), while the acquisition system is stopped with a delayed signal from the S1 or S2 beam scintillators. Note that while the sodium



iodide arrays are not utilized in this thesis, their inclusion in the trigger system is of importance. The transit time for the output signal of each detector in the target room to the acquisition system was approximately the same.

As each incident projectile ion passes through the pair of beam scintillators, both the S1 and S2 beam scintillators register a signal that is then split. One signal is sent to the constant fraction discriminator (CFD) for use in the trigger system, while the second signal is delayed and sent to a QDC. If the beam scintillator signal directed to the CFD surpasses the internal threshold, a logic NIM signal is delayed and sent to the TDC. A second, logic NIM signal is simultaneously sent to an *AND* coincidence gate, which fires a logic signal when the two beam scintillator signals are in coincidence. This logic signal is then sent to an *OR* coincidence gate.

The anode signal of each OLS pulse is passively split in two: one signal is directed to the CFD, while the other signal is fed into the pulse shape discrimination (PSD) module, which actively splits the incoming OLS signal into four signals. Two of the four signals are attenuated, which allows for the detection of higher pulse height events. Additionally, a pair of attenuated and un-attenuated signals are delayed such that only the first 20 to 35 ns of the analog signal will fit into the 200-ns integration gate of the QDC. Each of these four signals is then connected to a QDC. The integrated charge of the delayed signals will be referred to as the “short gate QDC” signals, while the total integrated charges are the “long gate QDC” signals. The comparison between the amount of charge in the short and long gates is later used in PSD to further identify particle events.

It should be noted that the six OLS are operated at less-than-ideal voltages to also allow for low-energy (<5 MeV) separation between neutron and gamma ray neutral particle events with PSD. Since neutral particles are minimally ionizing, this necessitates higher operating voltages. This is at odds with the detector’s sensitivity to the highly ionizing light ion events. At the OLS operating voltages (Table 4), the un-attenuated light ion event signals are beyond the voltage range serviceable by the QDC: these larger signals are all added to the overflow bin. Use of the attenuated signals reduces their amplitude by an internal factor set by the PSD module, which means the attenuated signals fit within the range of the QDC and events are recorded on-scale. The QDC signals used in the light ion analysis for this work are all attenuated signals.

Like with the beam scintillators, the OLS logic NIM signal is then sent to an *OR* coincidence gate after the CFD. Since the S1 and S2 coincidence signal theoretically arrives at the *OR* coincidence gate first, any subsequent OLS or CS event in this gate results in the creation of a 200-ns acquisition gate. This gate is then used as the charge integration gate for the QDCs, and as the start signal for the TDC TOF data acquisition.

IV.3 Measured Event Selection

IV.3.1 Valid Event Selection

Valid events are neutral or charged ion events detected by the OLS that set the trigger for the acquisition system. These events may be sorted from the total event list by filtering the data through a series of gates or graphical cuts using the ROOT Data Analysis Framework. After the valid events are separated, additional techniques are performed to identify the contributions from specific light ions, and then convert the resulting yield spectra to double differential thick-target (DDTT) light ion yields versus kinetic energy.

First, the charge deposition in the two beam scintillators is analyzed to eliminate invalid source particles. An example of this comparison is shown in Figure 10 for 400 MeV/N iron projectiles incident on all aluminum US target thicknesses. The ideal charge deposition between the two detectors should be correlated nearly 1:1, indicating that incident projectiles deposit roughly the same amount of energy in both beam scintillators. However, partial or higher-than-expected energy deposition may occur, and those events must be eliminated from the analysis. For example, the projectiles may fragment upstream from or in the first beam scintillator, resulting in the diagonal and horizontal features, respectively, seen in the left region of Figure 10. Additionally, the diagonal feature seen in the upper right portion of Figure 10 may be attributed to double hit events which occur when two projectiles strike the beam scintillators at the same time but their charge deposition only registers as a single event. A graphical contour, shown in Figure 10, was drawn around the events that deposited roughly the same amount of charge in the upstream beam scintillators, excluding the invalid events. This contour cut is referred to as the good beam cut; one good beam cut is made per beam species for all relevant projectile-target systems.

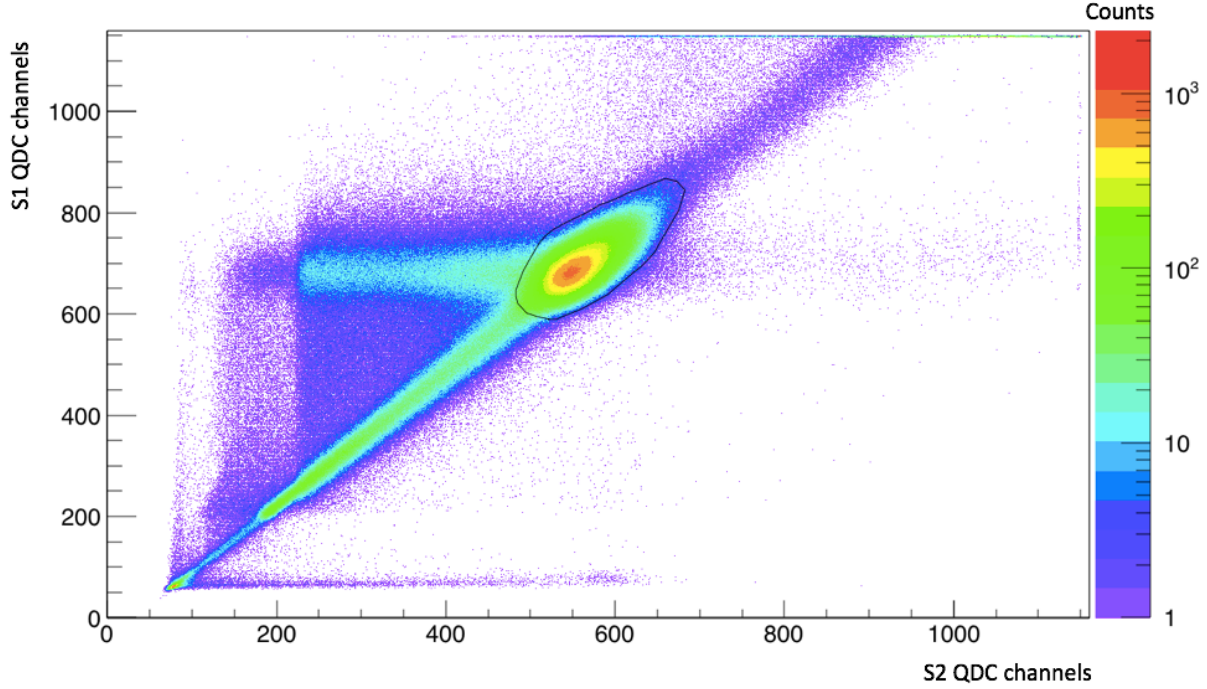


Figure 10. Charge collected in the two beam scintillators for 400 MeV/N iron on all Al US targets.

Next, events in the OLS of interest that set the acquisition trigger are selected using the recorded TDC spectra. A histogram of the TDC spectrum for 400 MeV/N iron projectiles incident on all aluminum US target thicknesses in the 10° OLS is presented in Figure 11a. The peak at approximately channel 225 is known as the self-time peak, and it is indicative of the events that set the acquisition trigger in the 10° OLS. For events that set the acquisition trigger, the timing difference between the start and stop signals is fixed, resulting in a peak at a fixed position in the TDC spectra. Events that do not set the acquisition trigger have timing information outside of the self-time peak and are eliminated with the self-time cut. This process is repeated for each liquid scintillator.

After the invalid source particles and mis-timed events are filtered out of the total event list, the charged and neutral particle event contributions are separated using the veto cut. This veto cut was taken by considering the charge deposition spectra of the thin veto detectors that directly covered the front face of the OLS. The QDC spectrum of the front veto detector for 400 MeV/N iron

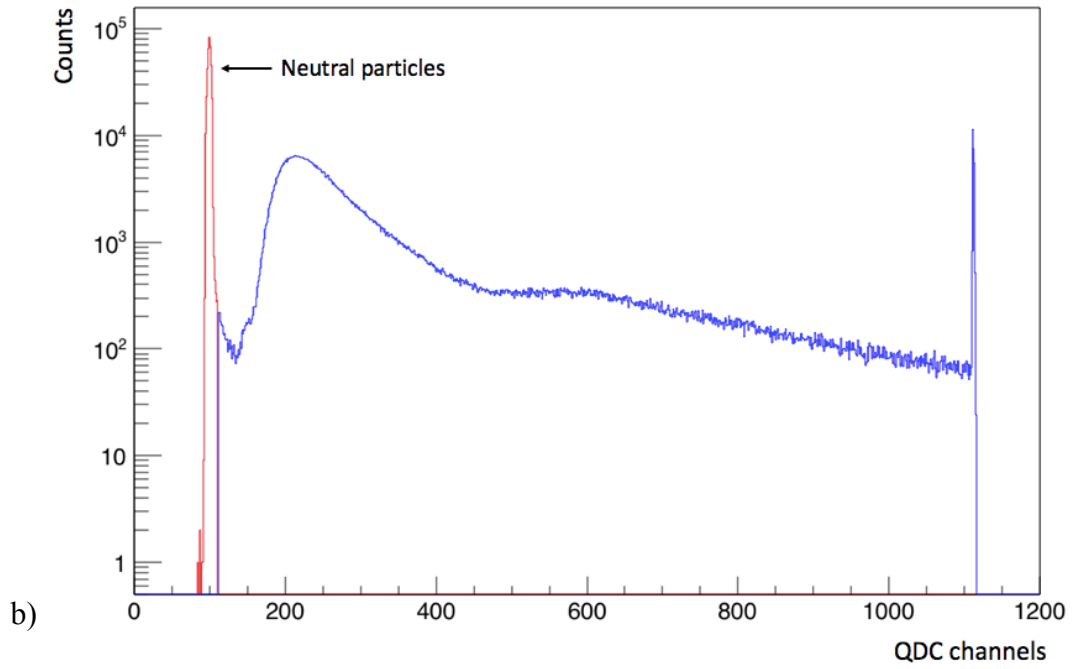
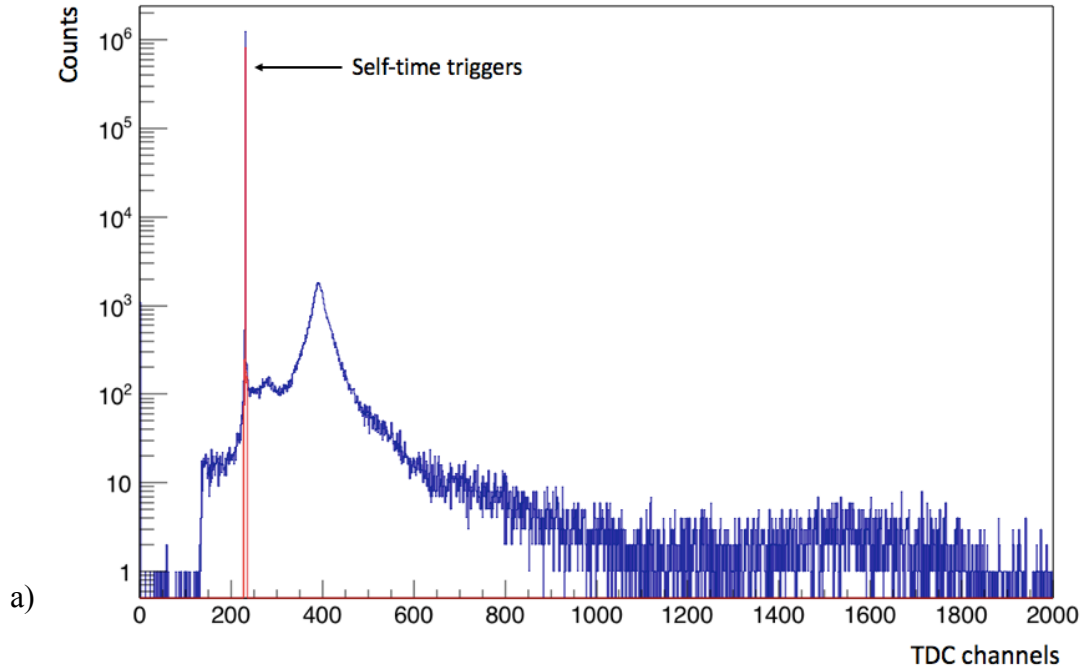


Figure 11. 10° OLS a) TDC spectrum used to identify particle events that set the acquisition trigger and b) QDC spectrum of charge collected in the veto plastic scintillator covering the front face of the OLS; 400 MeV/N iron on all Al US targets.

projectiles on all aluminum US target thicknesses at 10° is presented in Figure 11b. The veto QDC spectra are characterized by a sharp peak to the left known as the pedestal peak. This pedestal peak is populated during either a neutral event or during a non-event, indicating that all charge deposition to the right of the peak is attributable to charged particle events. Any event that registered above approximately channel 175 for the 10° front veto detector and is subsequently detected in the 10° OLS is considered a valid charged particle event. This process is repeated for each liquid scintillator's front veto detector. Neutral events are used later in Section IV.4.1 to calibrate the TDC spectra.

IV.3.2 Light Ion Identification

Light ion events were selected by plotting either the integrated charge in the long gate or short gate QDC of an OLS versus the TDC timing spectrum from the S1 beam scintillator. The light ion identification histogram for 400 MeV/N iron on all thicknesses of aluminum US target at 10° is illustrated in Figure 12a. Recall, the reverse triggering feature of the acquisition system indicates that events with fast TOF will appear with higher channel numbers on the x-axis. TOF decreases from left to right on the horizontal axis, and thus kinetic energy increases from left to right.

The detection signature of the five light ions most prominently observed in Figure 12a represent a continuum of energy deposition signatures for each particle. Each of these energy deposition signatures has three distinct features. The left, upward-sloping section is populated by events in which the particle deposited its full kinetic energy in the active volume of the OLS. The ensuing events to the right of this section punch through the detector, depositing decreasing amounts of charge in the active volume as their kinetic energies increase. The maximum point of energy deposition at the point where these two sections meet, is known as the punch-through-point. Particles at the punch-through-point have ranges equal to the length of OLS active volume. Comparison of punch-through-points of the deposition signatures on the light ion identification histograms allows for the assignment of each deposition signature's events to the responsible light ion.

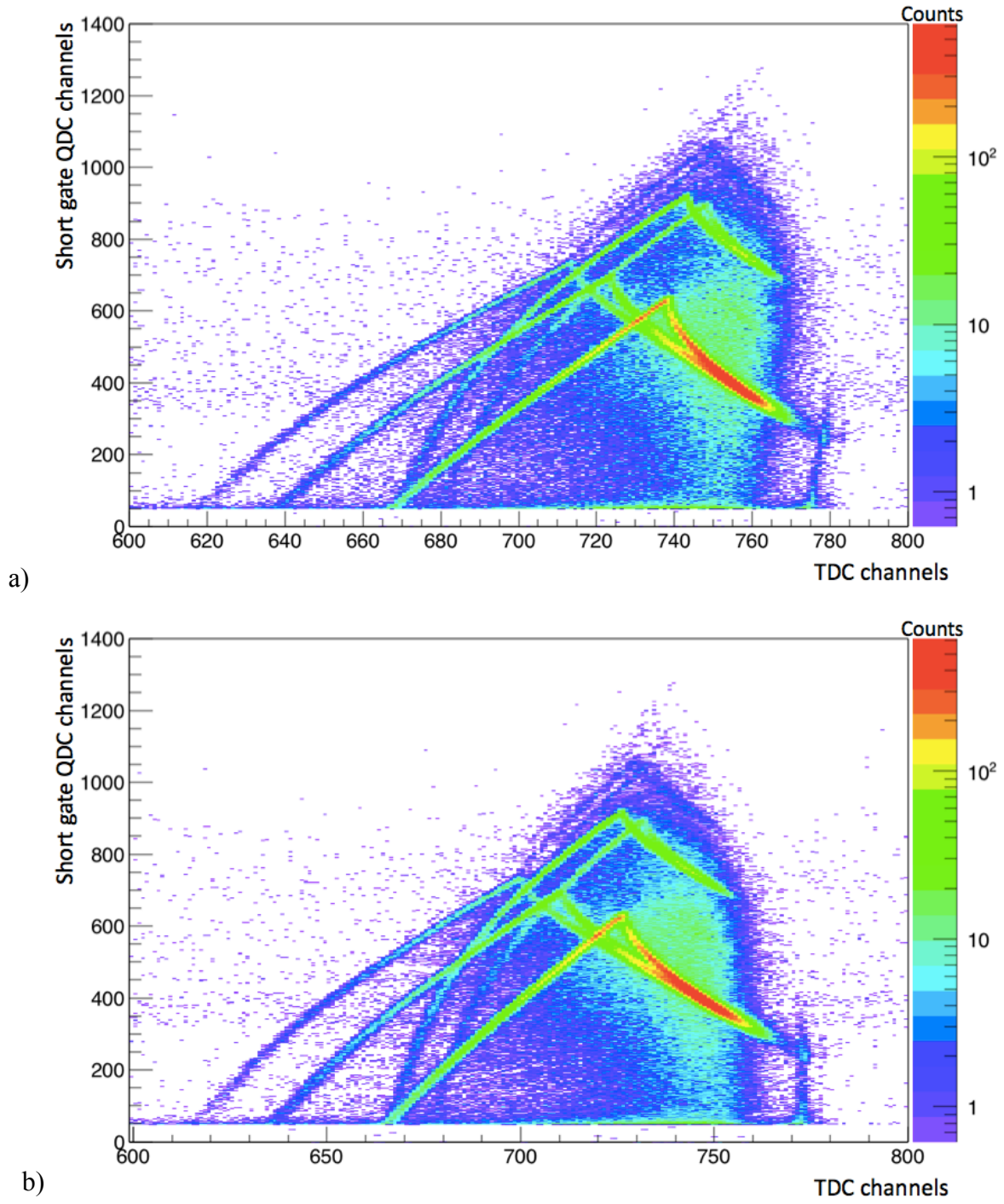


Figure 12. Light ion identification histograms for 400 MeV/N iron projectiles on all thicknesses of Al US targets at 10° , for a) the original data exhibiting time-walk as a function of QDC channel and b) the time-walk corrected data.

To assign the deposition signatures a light ion species, one relates the punch-through-points to the range of these light ions. The range (R) of light ions j and k with identical velocities moving in the same medium of volumetric mass density ρ , may be related using their charge (Z) and mass numbers (A) by equation 1:

$$(R\rho)_k = (R\rho)_j \frac{(A/Z^2)_k}{(A/Z^2)_j} \quad (1)$$

The range of light ions at the punch-through-point would be 11.1 and 11.5 g/cm² for EJ-301 and EJ-309, respectively. Using the stopping power and range data tables generated by SRIM [24] for xylene, the kinetic energy of each light ion at the punch-through-point by relating the range of the light ion to the range of a proton in equation 2:

$$(R\rho)_{proton} = (R\rho)_j \left(\frac{Z^2}{A}\right)_j \quad (2)$$

The punch-through-point energies for light ions using the SRIM data related by equation 2 are presented in Table 6 in kinetic energy per nucleon. The punch-through-points of the heavier ions will have higher channel numbers on the energy deposition scale (y-axis) because the total kinetic energy deposited is proportional to the number of nucleons in the ion. For further clarification on how these energies are manifested on the light ion identification histograms, the TOF for the light ion punch-through-points at each detection position are displayed in Table 7. For the 10° detector, the fastest of the lower three energy deposition signatures is caused by protons, while the fastest of the upper pair is caused by helium-3. The TOF of protons and helium-4 are nearly identical, which is expected since the z^2/A relation of these two particles are equal. However, it is seen in Figure 12a that these punch-through-points do not have identical TDC channel values if projected down. This is a result of time-walk produced by the CFD modules. This effect is rectified using the procedure in Section IV.3.3, and the results of the correction are seen in Figure 12b, where the proton and helium-4 punch-through-points are now aligned.

Table 6. Energy of light ions at punch-through-points.

Light Ion	Kinetic Energy (MeV/N)	
	EJ-301 OLS (10° – 45°)	EJ-309 OLS (80° – 135°)
Proton	123.69	130.42
Deuteron	83.76	88.27
Triton	66.89	70.44
Helium-3	145.65	153.58
Helium-4	123.69	130.42

Table 7. TOF of light ions at punch-through-points.

Detector	Light Ion	TOF (ns)		
		20 g/cm ²	40 g/cm ²	60 g/cm ²
10°, 30°, 45°	proton	20.94	20.90	20.85
	deuteron	24.71	24.66	24.60
	triton	27.28	27.23	27.16
	helium-3	19.58	19.55	19.50
	helium-4	20.88	20.85	20.80
60° and 80°	proton	17.14	17.04	16.91
	deuteron	20.20	20.08	19.92
	triton	22.30	22.16	21.98
135°	proton	13.72	13.66	13.58

IV.3.3 Time Walk Correction

The measured timing information needed further adjustment to correct for time walk. Time walk occurs when the timing of the logic signal from the CFD is influenced by the amplitude of the input pulse. Time walk was evident in Figure 12a in two noticeable ways. First, the measured punch-through-points for protons and helium-4 differ by nearly 10 TDC channels. In reality, the calculated punch-through-points have identical kinetic energies per nucleon, meaning they should have near identical TOF values. Second, minimally ionizing events recorded near the prompt gamma channel (the region near TDC channels 770-780 and QDC channels 0-400) exhibit an upward slant, falsely indicating that events depositing more charge arrive faster than the prompt gammas. If these time walk-influenced energy deposition signatures were projected onto the TDC timing axis without alteration, the events would populate the incorrect TDC bins, and would have incorrect TOF relative to the prompt gamma peak. The centroids of prompt gamma events on the TDC axis are unaffected by the time-walk feature. The conversion of the TDC axis from channel to TOF in nanoseconds is further explained in Section IV.4.1.

The time-walk adjustment followed the procedure laid out by Heilbronn *et al.* [25]. Both neutral and charged events were included on the two-dimensional QDC versus TDC histogram typically used to select light ions. Events associated with prompt gammas (in the TDC range of channels 770–780) were selected using a graphical cut. These events were further divided into slices on the QDC axis, with the QDC range for each slice shown in Figure 13 for 400 MeV/N iron projectiles on all thicknesses of aluminum US target at 10°. Each slice in Figure 13 was then projected onto the TDC axis as shown in Figure 14a. The correlation between the TDC centroid within each QDC range and the midpoint of the QDC slice was found via linear regression. An example of the linear fit to the slice centroid data is shown in Figure 14b for the 400 MeV/N iron projectile on all thicknesses of aluminum US target at 10°. A ROOT macro was created [26] to cycle through the measured data on an event-by-event basis. This macro used the slope m of the linear regressions to correct the TDC channel values as function of the QDC channel value, using equation 3, and this process was repeated for each projectile system at the six detector locations.

$$TDC_{new} = TDC_{original} - \left(\frac{QDC}{m} \right) \quad (3)$$

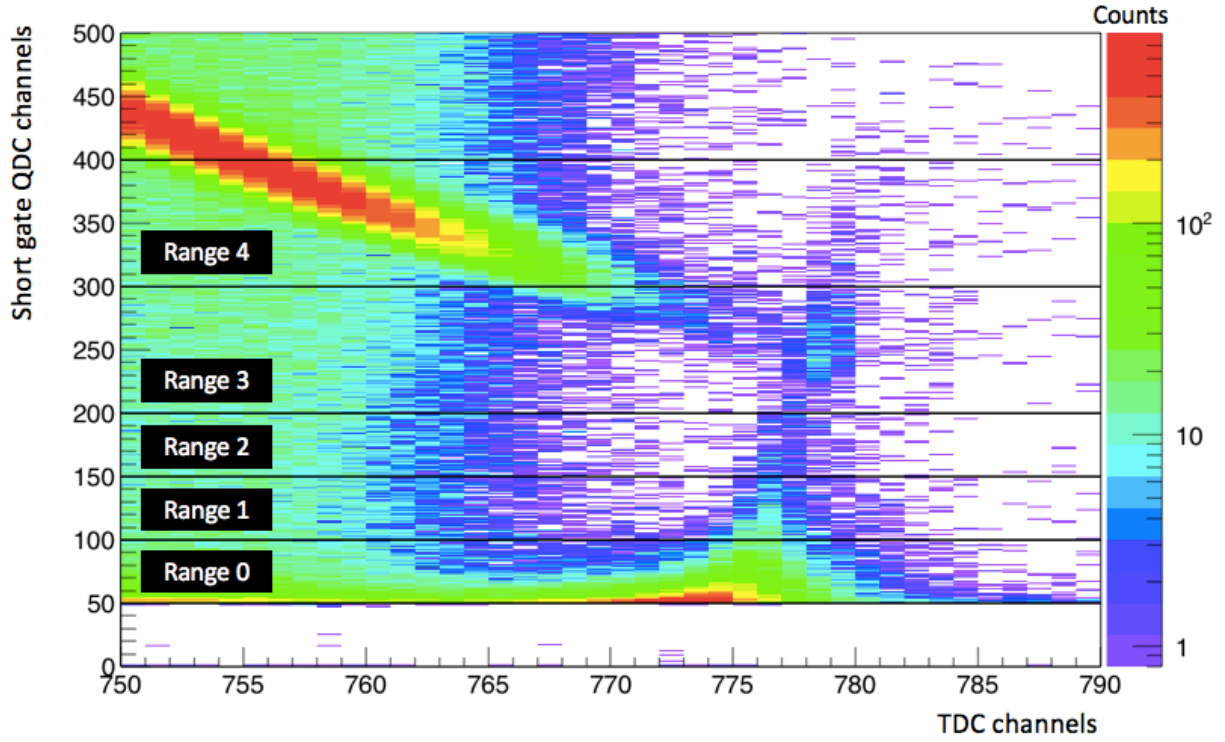


Figure 13. Illustrated slices of the QDC spectrum used to calculate the time walk correction factor; 400 MeV/N iron projectiles on all thicknesses of Al US target at 10° .

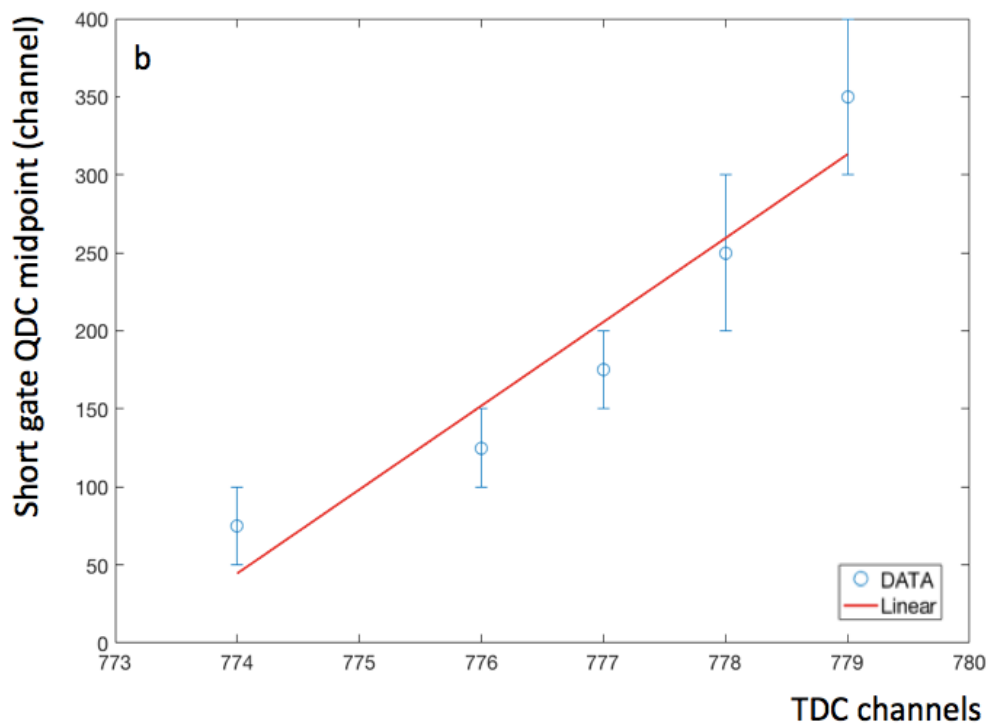
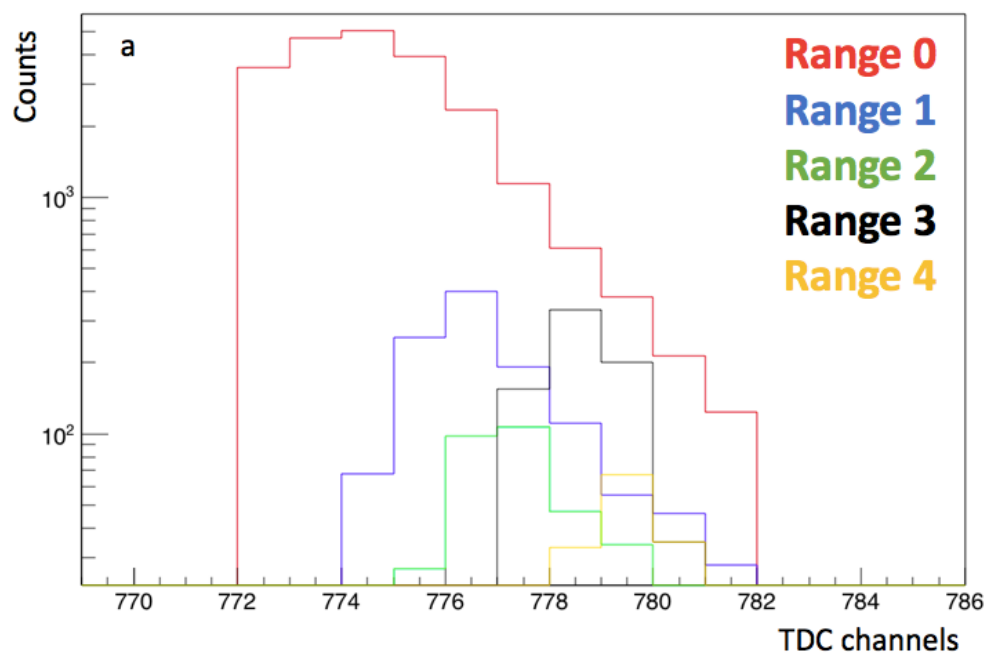


Figure 14. a) Projections of each QDC slice onto the TDC axis. b) Linear fit to the centroids of each QDC slice.

An example of the implemented time-walk correction is shown in the light ion identification histogram (Figure 12b) for 400 MeV/N projectiles on all thicknesses of aluminum US target at 10°. The TDC channel of the proton and helium-4 energy deposition signatures at the punch-through-points are now identical. The events near the prompt gamma signatures now have vertical QDC signatures. This correction ensures the timing information of the events selected in the particle identification contours will be independent of the magnitude of the charge deposition.

IV.3.4 Pulse Shape Discrimination

There are points on the light ion identification histograms where the energy deposition signatures of certain ions intersect with the signatures of other ions. Points of crossover on these histograms were resolved by using pulse shape discrimination techniques, as detailed for light ions detection by Kurosawa *et al.* [10]. This technique exploits the differences in the stopping power (dE/dx) of different light ions, and how this is manifested in the pulse output of the OLS. The shape of the pulse output of the OLS as a function of time is sensitive to the dE/dx of the particle generating the signal. Slower particles with high dE/dx will deposit more charge in the slower components of the OLS pulse, as the particles approach the end of its range. Light ions with the maximum dE/dx in the OLS active volume are those with the punch-through kinetic energy. Light ions with kinetic energies higher than the punch-through kinetic energy deposit less charge in the slower components of the pulse when compared to light ions with kinetic energies lower than the punch-through kinetic energy. This results in a larger amount of charge concentrated in the short gate when compared to the slower light ions that deposit the same amount of charge in the long gate [10]. The signal delays introduced by the PSD module seek to capitalize on these features. The following PSD techniques thus compare the amounts of charge integrated in the resulting short and long gates created by the PSD module.

Comparison of the short and long gate charge integration for 400 MeV/N iron on all thicknesses of aluminum US targets at 10° is shown in Figure 15a. While this figure is a close up of the histogram section with the most distinctive features, the trends are consistent throughout the entire spectrum. The correlation between charge collected in the short or long gates is consistent for all

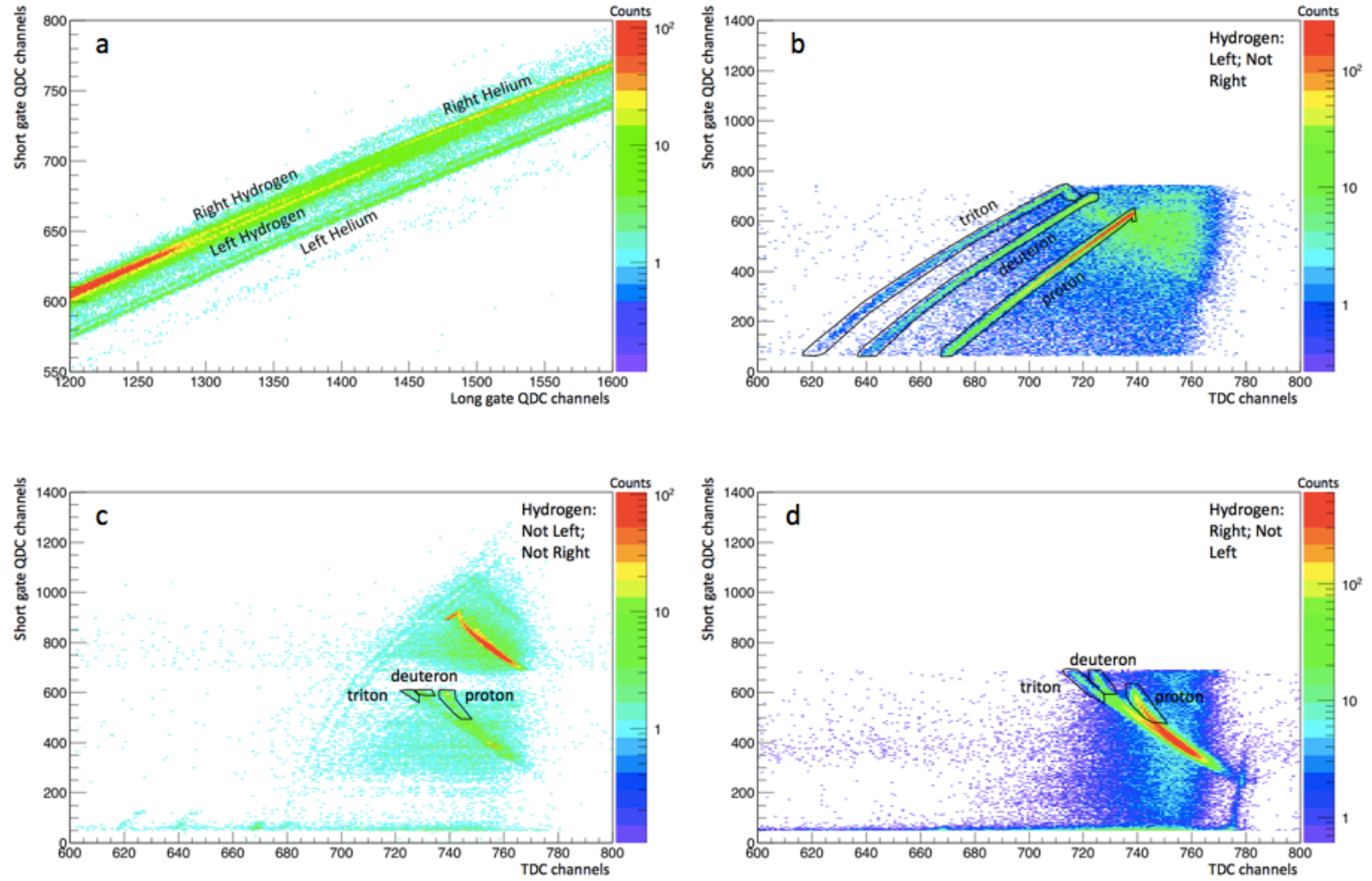


Figure 15. 400 MeV/N iron projectiles on all Al US thicknesses measured at 10° . a) PSD spectrum shows the separable elements; (b-d) Light ion identification histogram with PSD cut applied, as indicated in the top right corner, and particle identification contours.

the events observed. It is simplest to imagine the streaks as lines with identical slope that differ in their x-intercept. The observed streaks that appear lower on the y-axis (for example: the streak labeled “left helium”) have higher dE/dx , depositing more charge outside of the short integration gate when compared to the faster particles. This technique made elemental isolation of hydrogen and helium events possible, but did not have sufficient resolution to separate the hydrogen isotopes. Isotopic isolation of helium events was possible for light ions below the punch-through kinetic energy.

Graphical contours were drawn to select events contained in the streaks shown in Figure 15a. The streaks corresponded to light ion events on either side of the punch-through-point (Figure 12a). These PSD contours were then applied to the light ion identification histograms for each projectile-target system to help eliminate points of crossover between the light ion energy deposition signatures. The pair of left and right elemental contours were combined using Boolean logic to ensure no events were counted twice. The application of the PSD contours to the light ion identification histogram are presented in Figure 15b to Figure 15d, with the Boolean logic gates used to produce these figures indicated at the top right. Application of these PSD contour cuts to the isotope identification histogram successfully eliminated the points where energy deposition signatures crossed.

The PSD technique was essential for isotope identification in the 10° to 45° OLS results because there were always at least two light ion signatures present in the light ion identification histograms at these detector positions. PSD was not necessary for the 60° to 135° OLS since generally only protons events exhibited energy deposition signatures above and below the punch-through kinetic energies at these detector positions. Deuteron and triton events detected at these wide-angle positions did not have any discernable events above the punch-through kinetic energy.

Once the crossover points on light ion identification histograms were resolved using PSD, the final particle identification graphical cuts were drawn around the resulting isolated energy deposition signatures. This allowed for effective identification of the proton, deuteron, triton, helium-3, and helium-4 light ion events. The events contained in these particle identification cuts were then projected down onto the TDC timing spectrum to generate the DDTT light ion yields versus TOF

histograms. The conversion of the x-axis from TOF in channels to TOF in nanoseconds, and then subsequently to energy, will be described in the following sections.

IV.4 TDC Channel-to-Energy Conversion

IV.4.1 TDC Channel-to-TOF

Neutral particle events that were separated out by the veto paddles were used to calibrate the TDC axis from channels to nanoseconds. This meant the un-shadowed (uncovered) and the shadowed runs were needed to eliminate the contributions of any room-scattered neutral particles in the S1 TDC histogram. Un-shadowed run data were summed and shadowed run data were then subtracted to eliminate the background events. The background-adjusted TDC spectrum of neutral events for 400 MeV/N iron on 20 g/cm² aluminum US target at 10° is presented in Figure 16. The peak at TDC channel 773 represents the prompt gammas generated in the US target during incident projectile interactions. Prompt gammas are an effective timing signature because the velocity of the gamma ray is known and constant. Using the velocity and the measured flight paths from Table 5, the TOF for prompt gammas are calculated and presented in Table 8. The TOF of the prompt gamma ray is assigned to the centroid channel of the prompt gamma events as measured on the S1 TDC axis. This process was repeated for each projectile-target system at all detector positions. The prompt gammas centroids are listed in Table 13 through Table 15 (Appendix I).

Subsequent TDC channels are spaced linearly in time by the ns/channel division also listed in Table 8. The time per channel division is determined prior to the experiment utilizing the acquisition system and adding known amounts of cable delay. A pulser sends a signal through the acquisition system, which populates a single channel on the TDC histogram. The cable delay is increased by a known amount and the newly populated TDC channel is recorded. This is repeated at least three times to form a calibration curve. The slope of the linear fit to these three points is the ns/channel value of the TDC module. Since the TOF of the prompt gamma centroid channel is now known, the remaining TDC channels may be converted to TOFs using the ns/channel calibration. The new TOF axis may then be converted from ns to energy using the data obtained by the process described in the next section.

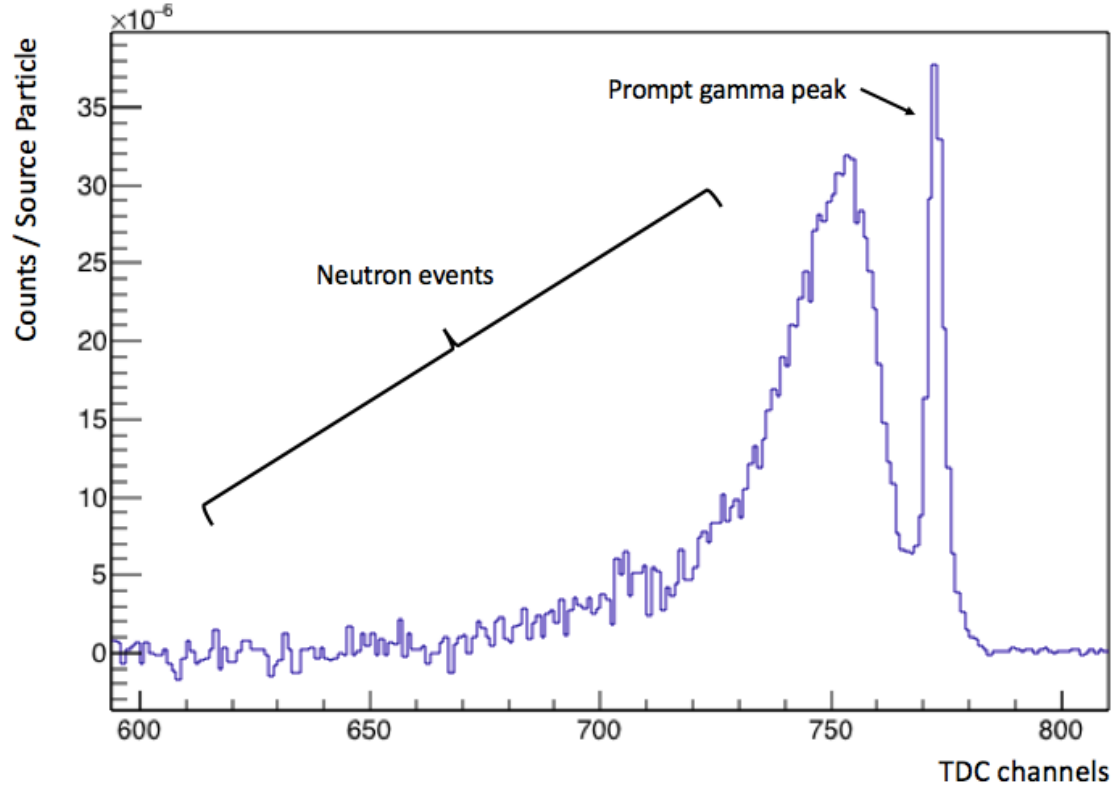


Figure 16. Neutral event TOF at 10° for 400 MeV/N iron on 20 g/cm^2 Al US target. Time increases right to left.

Table 8. TDC time per channel division and prompt gamma peak times of flight as a function of angle.

Detector	Nanoseconds/Channel	Prompt Gamma TOF (ns)
10°	0.238	10.0
30°	0.237	10.1
45°	0.235	10.1
60°	0.232	8.40
80°	0.235	8.38
135°	0.229	6.71

IV.4.2 TOF-to-Kinetic Energy

To convert the TOF axis to kinetic energy for light ions, energy loss of the light ion as it traverses a material must be taken into consideration. The kinetic energy of interest is the kinetic energy of the light ion as it enters the active volume of the detector. In order to reach the active volume, the light ion must have enough energy to escape the US target, traverse the air between the US target and detector stand, then pass through approximately 0.6 cm of plastic scintillator veto paddle material and an additional 0.15 cm of aluminum detector housing. The stopping power dE/dx of a light ion with charge number z moving at velocity βc , in a medium with electron density n (# electrons /cm³) and mean excitation energy I (eV), may be determined utilizing the simplified Bethe equation (4) in units of MeV/cm [27]. The quantity c is the speed of light in a vacuum.

$$-\frac{dE}{dx} = \frac{5.08 \times 10^{-31} z^2 n}{\beta^2} \left[\ln \left(\frac{1.022 \times 10^6 \beta^2}{1 - \beta^2} \right) - \beta^2 - \ln(I) \right] \quad (4)$$

A generalized stopping power program was written using equation 4. This program divided the measured flight paths in Table 5 into thousands of smaller steps. The measured flight path in the US target was determined with this program. The initial kinetic energy considered by the program must have a range at slightly greater than this amount of target material. Particle ranges were determined using NIST range tables [28]. The time for the light ion to traverse each small step was calculated, and the dE/dx was applied at the end of the step. This calculation was done continuously until the particle depleted its kinetic energy or reached the OLS active volume. The TOF and final kinetic energy were recorded once the active volume was reached. These calculations were performed continually for incrementally higher light ion kinetic energies up to at least 800 MeV/N. This process was repeated for each US target thickness and each detector position for protons, deuterons, tritons, helium-3, and helium-4 for three production points. The assumption of the three production points, the upstream surface of the US target, the target center, and the downstream surface of the US target, factored in the uncertainty in the light ion production point. The importance of production point uncertainty will be discussed in detail in Sections V.3.1 and V.3.3.

These calculations produced data tables that contained the energies of light ions impinging on the front surface of the OLS active volume, as well as their associated TOF. An example of the data set for the light ions emerging from a 20 g/cm² aluminum US target at 10° is shown in Figure 17. The TOF axis for each projectile-target system was converted to a total kinetic energy (MeV) by performing a linear interpolation on these tabulated values. This resulted in double differential thick-target light ion yields versus energy spectra.

IV.5 Energy Deposition Detection Efficiency

The detection efficiency was a measure of the mean energy deposition in the OLS active volume. This was estimated by using versions 2.82 and 2.88 of the PHITS [29] Monte Carlo transport code. A planar source of mono-energetic light ions was set incident on the outermost planar face of two concentric cylinders. The inside cylinder was xylene-filled to approximate the active volume of the OLS and the outer cylinder represented the aluminum containment. The transport calculations determined the fraction of source events that deposit the maximum energy in the liquid scintillator as determined by the light ion's stopping power. A T-deposit tally was used to histogram the energies deposited in the liquid scintillator in increments of 0.25 MeV. For all the simulations, the majority of the source particles had an energy deposition result contained within a single 0.25 MeV energy bin. This fraction of events exhibiting this ideal energy deposition behavior was subsequently used as the energy deposition efficiency. The energy deposition efficiency as a function of the incident proton, deuteron, and triton kinetic energies for both EJ-301 and EJ-309 scintillator liquids are presented in Figure 18a. Similarly, the energy deposition efficiency as a function of the incident helium-3 and helium-4 kinetic energies for EJ-301 are presented in Figure 18b in EJ-301, since helium light ions were not measured at the EJ-309 detectors. Separate simulations for the EJ-301 and EJ-309 liquid scintillators were necessary due their differences in density (Table 4). The minimum energy deposition efficiency was encountered at the punch-through-point kinetic energy for each light ion, exhibiting the influence of range straggling for particles with punch-through kinetic energies. The calculated midpoints for each kinetic energy bin of the DDTT light ion yields were used to tabulate additional energy deposition efficiencies

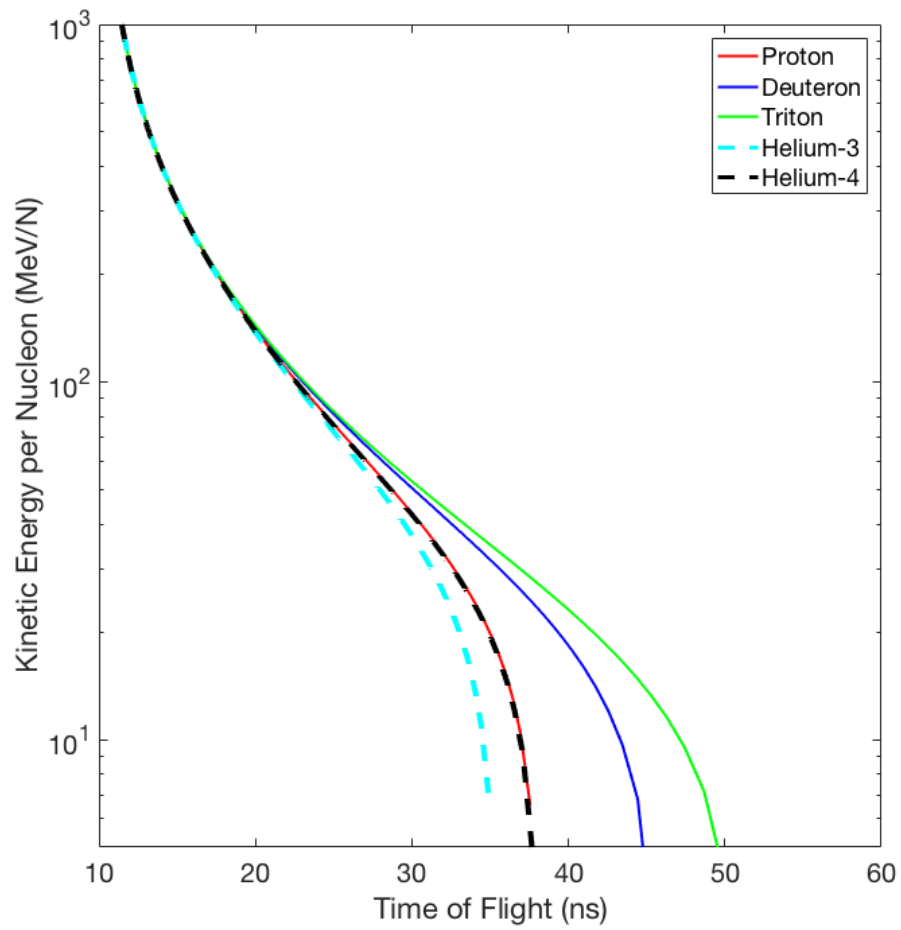


Figure 17. TOF to kinetic energy data for 20 g/cm^2 Al US targets for light ions incident on the 10° OLS.

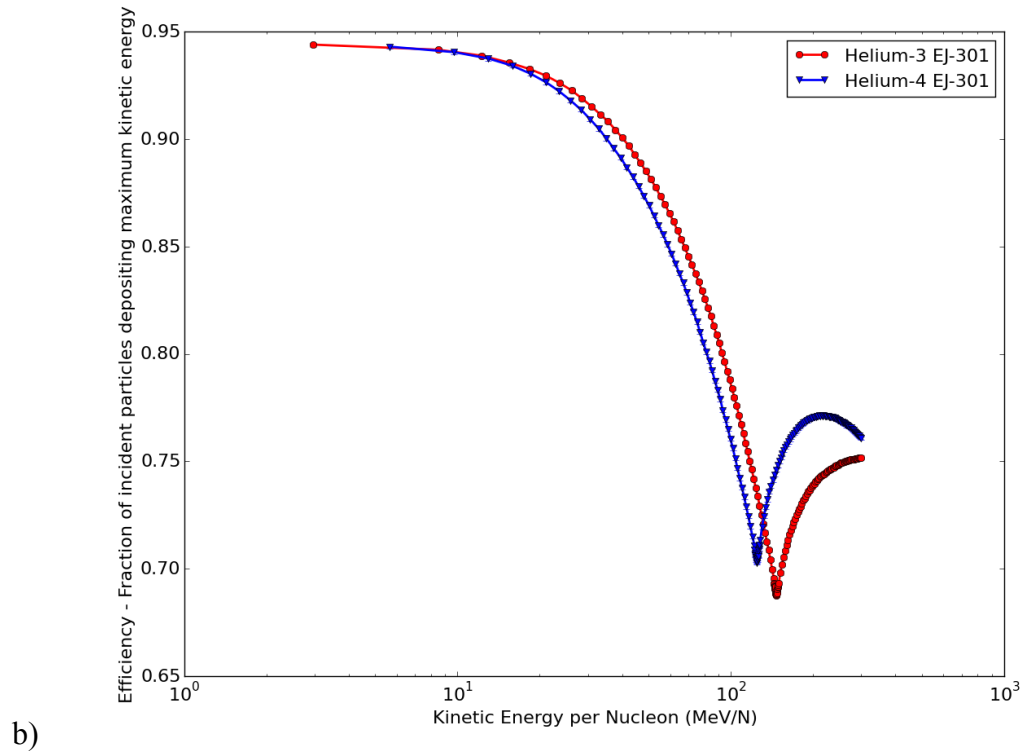
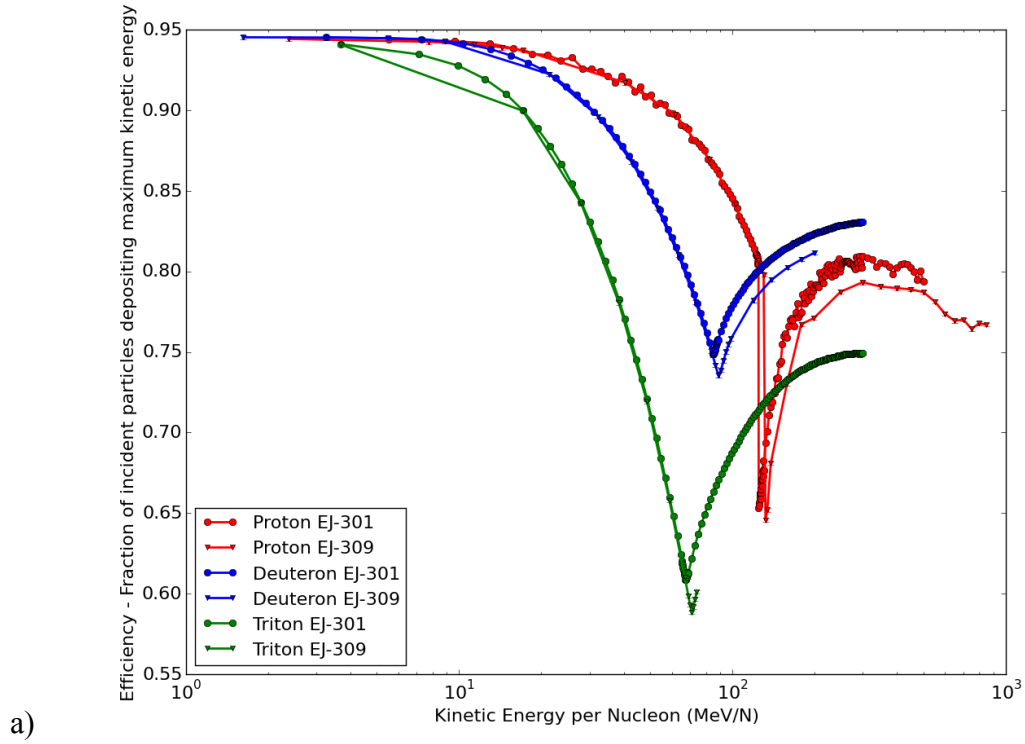


Figure 18. Simulated energy deposition efficiencies for a) protons, deuterons, and tritons and b) helium-3 and helium-4 ions in liquid scintillators.

via linear interpolation. These energy deposition efficiencies were then applied to the yield data in the final normalization steps.

IV.6 Monte Carlo Simulations

IV.6.1 MCNP

The Monte Carlo transport code MCNPX version 2.7.0 [30] was used to replicate the experiment, generating simulated DDTT light ion yields to compare to the experimentally measured quantities. MCNPX uses tabulated data for neutron interactions up to 20 MeV and otherwise relies on physics models to simulate the transport of nucleons, light ions, and heavy nuclei. The CEM (CEM03.02) and LAQGSM (LAQGSM03.03) physics models were selected for use, and are described in [31]. Nuclear interactions are modeled in distinct cascade, pre-equilibrium, and evaporation steps. The consideration of all three steps in high-energy reactions differentiates these models from pure cascade models [32]. CEM handles the transport of nucleons, while LAQGSM handles the transport of nuclei. These codes differ in their assumptions of the nuclear density of nucleons: CEM models the nucleus as a sphere with seven concentric zones of constant nuclear density within the zones, while LAQGSM uses a continuous nuclear density model. CEM does not take into account the decrease in nuclear mass and charge density as the reactions occur, while LAQGSM does consider that effect. This change in density is essential for reactions of heavier nuclei or any reaction at kinetic energies above 1 GeV [31]. For residual nuclei with $A > 13$, light ions are formed in pre-equilibrium ejections and coalescence mechanisms. The coalesce radii used in LAQGSM were universal, while a different set was used in CEM for reactions in the kinetic energy range of 0.3 to 1.0 GeV [31]. If the resulting nucleus is of $A \leq 12$, the Fermi break-up model is used to form any possible light ions [33].

The MCNP input geometry closely matched the NSRL target room. Along with the pair of targets and the six sets of OLS detector arrays; the air, walls, rail system, and target beam dump were represented to-scale to most realistically approximate the experiment. Simulations were run on the University of Tennessee's (UTK) Department of Nuclear Engineering computer cluster which utilizes MPI for parallelization. Simulations for the iron projectiles were run for 10^7 histories,

while simulations for the proton and helium projectiles were run for 10^8 histories. No variance reduction methods were utilized.

Light ion tracks were tallied using the SSW surface source read feature of MCNPX to generate a list of particle tracks crossing the surfaces of the OLS detectors. This method was employed over the built-in tally functions to allow analysis on an event-by-event basis which was more similar to the experiment methodology. This also gave the user freedom to manipulate the tally results after the conclusion of the simulation. The SSW feature outputs a binary file which is translated using the open source program MC-TOOLS [34] to text files. This text file was then used to populate a ROOT tree, allowing for seamless analysis of the simulation results on an event-by-event basis. An example of these analysis methods can be seen in Figure 19 for the proton yields from 400 MeV/N iron projectiles on 20 g/cm² aluminum US target between 10° and 135°. This image showcases the ability to plot all tally events as a function of the particle's TOF and kinetic energy. Note, the times on the vertical axes of Figure 19 are in shakes which is the default unit of time in MCNP (1 shake = 10 ns). This is essential for the comparison to the experimental measurements because it allows the user to isolate the particle tracks directly attributable to US target production. Particles originating in the US target will have directly correlated TOFs and kinetic energies, as seen in the calculations presented in Section IV.4.2. Results were tallied according to the F2 tally criteria used in MCNPX, which tallies each particle track crossing the OLS detector surface by the track's weight, w , divided by the cosine k of the track direction relative to the tallying surface normal [35]. The results of the tally are also scaled by the cross-sectional area of the detector face.

For the simulation results presented in this work, an additional criterion was set on the tally results which placed a restriction on the cosine k of the tracks entering the detector. Tracks must have a value of $k > 0.97$. This assumes the particle tracks entering the OLS and originating from the US target will be extremely forward directed. The effect of this track restriction can be seen in the simulated results in Figure 20 and Figure 21 for 400 and 800 MeV/N iron projectiles incident on 20 g/cm² aluminum US target at 10°. The right two panels (b and d) of Figure 20 show that the directionality restriction contains particle tracks that solely exhibit the correlated TOF versus energy characteristics calculated in Section IV.4.2. This directionality restriction effectively

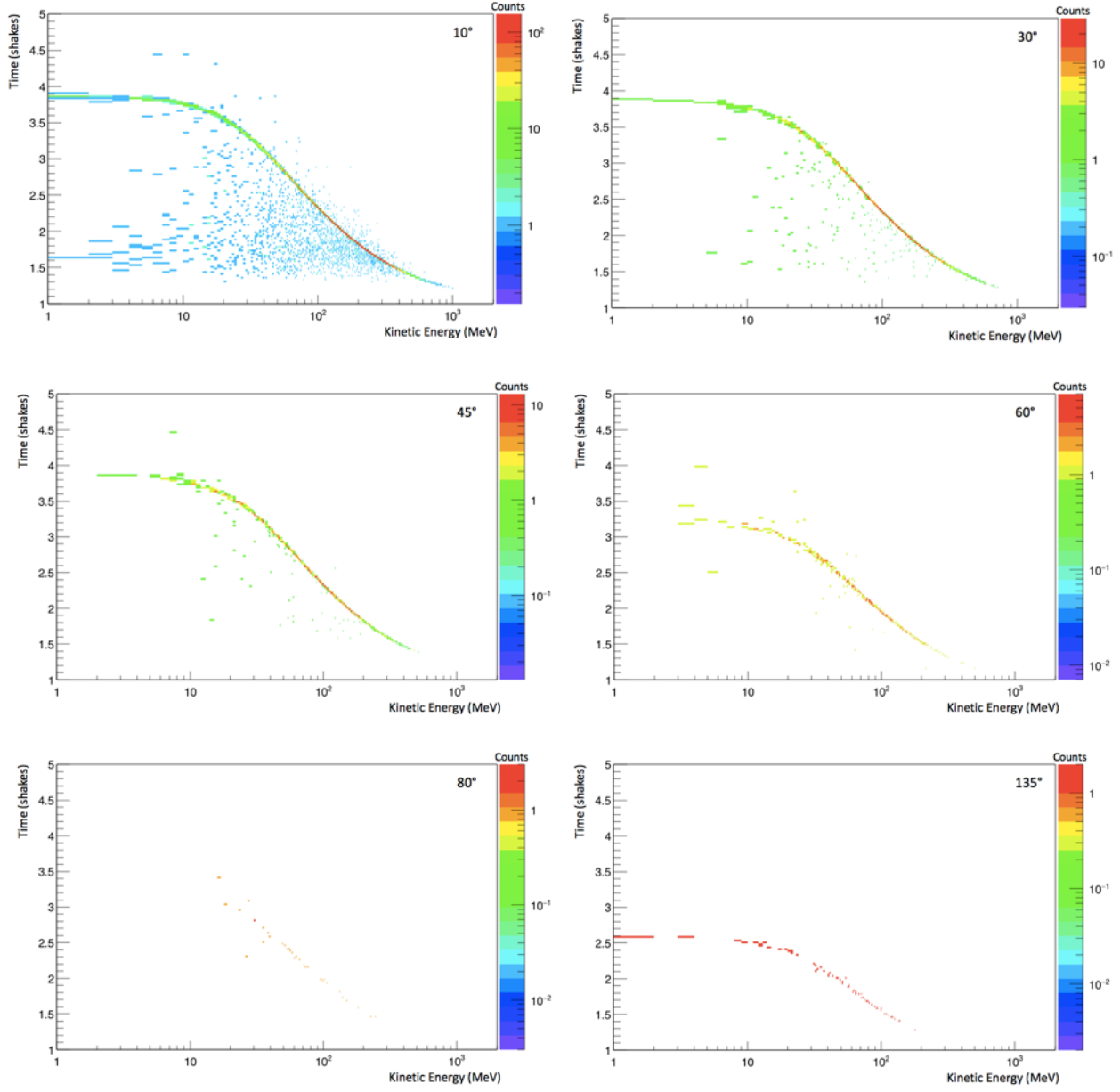


Figure 19. Simulated proton fluences for 400 MeV/N iron on 20 g/cm² Al US target between 10° and 135°.

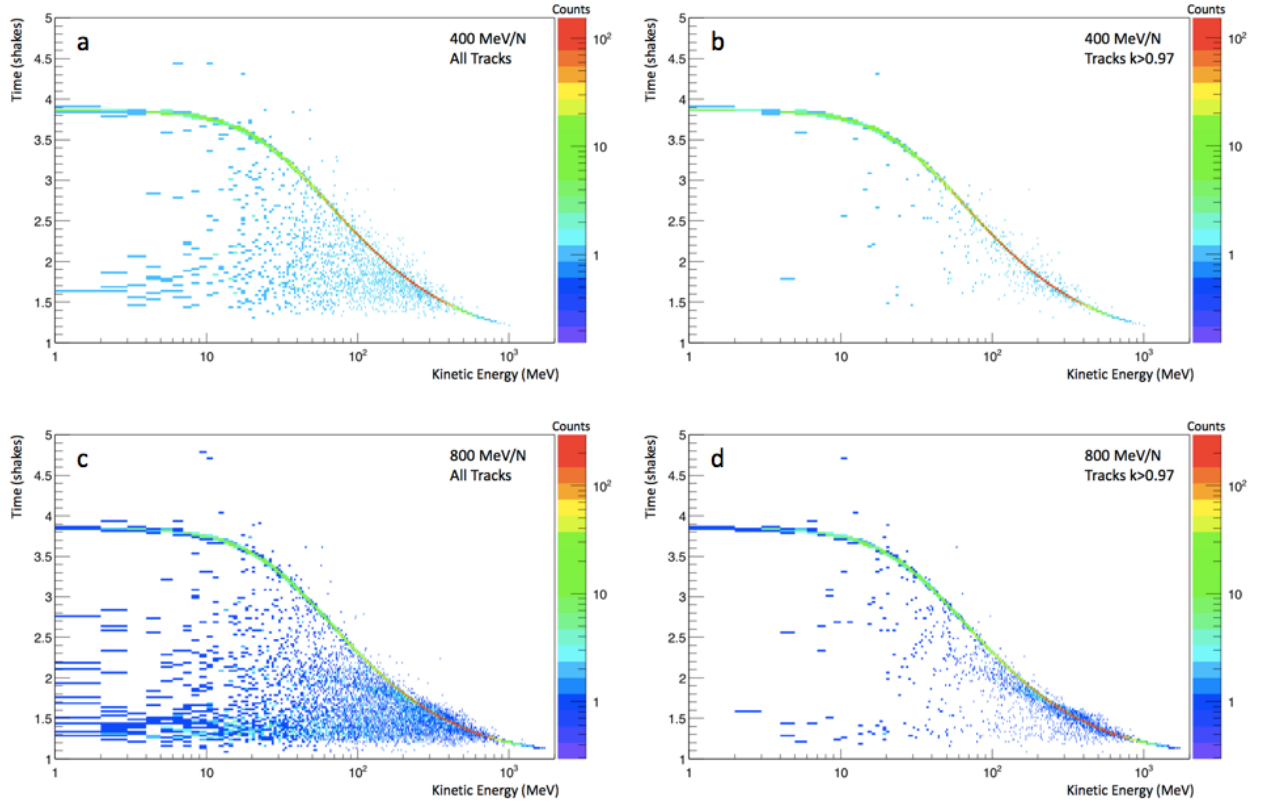


Figure 20. Simulated proton flux for 400 MeV/N iron on 20 g/cm² Al US target at 10° with a) all tracks and b) directionally restricted tracks. Simulated proton flux for 800 MeV/N iron on 20 g/cm² Al US target at 10° with c) all tracks and d) directionally restricted tracks.

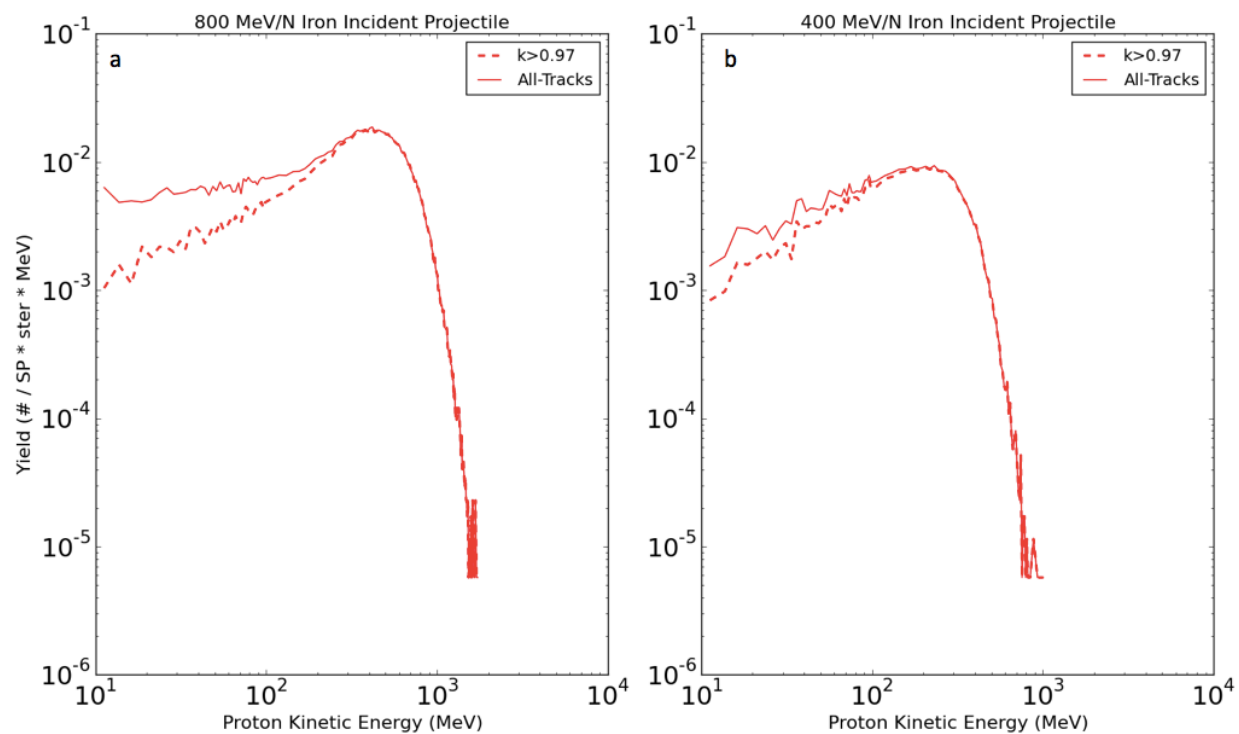


Figure 21. MCNP-simulated DDTT protons yields for a) 800 and b) 400 MeV/N iron on 20 g/cm^2 Al US target at 10° ; all proton tracks and directionally-restricted proton tracks.

eliminates the non-correlated contributions. Once projected on to the kinetic energy axis in Figure 21, it is seen that the non-correlated events have a significant contribution to the DDTT proton yields for 800 MeV/N iron projectile results below 200 MeV proton kinetic energy. This divergence in yield is less sharp in the 400 MeV/N iron projectile spectra. The directionality restriction is placed on all MCNP results subsequently shown in this work.

IV.6.2 Additional Monte Carlo Calculations

Additional transport models and physics model options were considered to compare the ability of the simulations to create all hydrogen and helium isotope light ions during transport through thick targets. To do this, only the iron and helium projectiles at both 400 and 800 MeV/N were considered on a single aluminum US target thickness of 20 g/cm². Additional MCNPX simulations were conducted using the ISABEL INC module [36], [37] to handle reactions of light ions below 940 MeV/N. This takes the place of the LAQGSM event generator, as previously described. These additional MCNPX simulations used the same tallying methodology noted above.

Additionally, simulations performed by the transport code PHITS version 2.82 [29] were used for comparisons to the MCNPX simulations of helium and iron projectiles on 20 g/cm² aluminum. PHITS utilizes JQMD [38] to handle the transport of heavy ions and INCL4.6 [39] to handle the transport of nucleons and light ions. These simulations were performed by Hui-Chen Wang, a fellow graduate student in UTK's Department of Nuclear Engineering, and a fellow collaborator on the Thick GCR Shielding project. These simulations utilized a ring-style detector to increase geometric efficiency and achieve better counting statistics. The ring geometry may be seen in Figure 22. The angles from the beam-axis to the rings are identical to the measurement geometry. The rings also had depths and widths consistent with the dimensions of the OLS used in the measurements. T-cross tallies were utilized to score the particle tracks entering the ring from the air-filled region directly in front of ring, which helped mitigate the contributions from the DS target. The comparisons of PHITS- and MCNP-simulated yields to the measured quantities will be discussed in Section V.5 and shown in Appendix III.

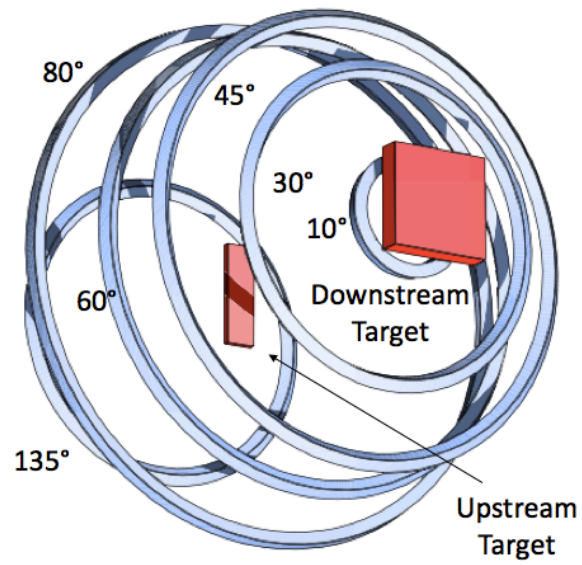


Figure 22. Ring geometry utilized by PHITS simulations to use in comparisons of iron and helium projectiles [40].

V. RESULTS AND DISCUSSION

V.1 Overview

The DDTT hydrogen (proton, deuteron, triton) and helium (helium-3, helium-4) isotope yield data measured between 10° and 135° for all projectile-target systems are displayed in Figure 35 through Figure 78 in Appendix II. Each measured DDTT yield is plotted at the midpoint of the energy bin, with horizontal error bars representing the energy uncertainty. The vertical error bars are indicative of the statistical uncertainty in the yields, with systematic uncertainties in the yields reported only in the text (Section V.3.1). If no error bars are seen, they are smaller than the plotting symbols. These plots also include comparisons to DDTT yields simulated by the MCNP transport code. Error bars are not plotted for the Monte Carlo-simulated results, and are instead discussed in Section V.3.2. Additional comparisons were conducted for the 400 and 800 MeV/N iron and helium projectiles incident on the 20 g/cm^2 US target measurement datasets. Here, the measured hydrogen and helium isotope yields were compared to MCNP's LAQGSM and ISABEL physics models, and PHITS. Results are shown in Figure 79 through Figure 95 in Appendix III.

A summary of the detector positions where light ions were measured for each of the six projectiles studied is presented in Table 9. Protons were measured at all six detector positions for each projectile. Deuterons were observed at the three forward-most detectors (10° to 45°) for all projectiles. For projectiles with mass numbers greater than 1 ($A > 1$), the 10° to 45° detectors measured the three hydrogen isotope light ions, while the 10° and 30° detectors additionally detected the helium light ions. In all, 282 DDTT yield spectra were measured. Of that total, 258 were deemed satisfactory if they had at least four data points for each data set resulting from bombardments of the three US target thicknesses. Measured datasets that are compared to additional physics model calculations (Appendix III) are marked with an "O" in Table 9.

Table 9. Summary of measured light ions for each projectile-target system

Projectile, Kinetic Energy	Fe 400 MeV/N						Fe 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Protons	O	O	O	O	O	O	O	O	O	O	O	O
Deuterons	O	O	O	O			O	O	O	O		
Tritons	O	O	O				O	O	O			
Helium-3	O	O					O	O				
Helium-4	O						O	O				

Projectile, Kinetic Energy	He 400 MeV/N						He 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Protons	O	O	O	O	O	O	O	O	O	O	O	O
Deuterons	O	O	O	O			O	O	O	O		
Tritons	O	O	O				O	O				
Helium-3	O	O					O	O				
Helium-4	O	O										

Projectile, Kinetic Energy	H 400 MeV						H 800 MeV					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Protons												
Deuterons												
Tritons												
Helium-3												
Helium-4												

	Particle observed and produces viable double differential particle yield spectra for each U.S. target thickness
	Particle observed, does NOT produce viable spectra for each U.S. target thickness
	Particle NOT observed
O	20 g/cm ² US target data used to compare to additional physics model calculations

V.2 Limitations in the Experiment and Analysis

V.2.1 Limits on the Measureable Kinetic Energy Range

The multitude of light ions incident on the detectors, especially the forward-most detectors, limited the ability to discriminate light ion events at high kinetic energies. This issue is best demonstrated with the light ion identification histogram for the 10° OLS from 400 MeV/N iron projectiles incident upon all thicknesses of US target in Figure 23. The “right” PSD cut which isolates high-energy events is applied, as discussed in Section IV.3.4. Here, the graphical contours used to select the events attributable to specific light ions are marked in black. The contours rendered in red indicate events where isotope identification is not possible: the left-most region contains events that are indicative of either deuterons or tritons, while the right-most region contains events caused by all three hydrogen isotopes. This convergence sets the upper limit on the maximum kinetic energy for the DDTT yield spectra measurements. The information provided by the acquisition system of this experiment does not make further identification of events in these red regions possible with any certainty.

The DDTT yield spectra were constructed by projecting the number of events contained within the particle identification contours onto the horizontal, TOF axis. These spectra understate the true yields at the lowest TOFs since the particle identification contours do not fully sample the energy deposition spectrum in each time bin. This is due to the interference of events from other particle types as the contours merge. A similar under-sampling effect is also noted for events with the slowest TOFs. How this is expressed in a DDTT yield spectrum is shown in Figure 24, showcasing the DDTT yields of protons, deuterons, and tritons measured at 10° for 400 MeV/N iron projectiles striking the 20 g/cm^2 US aluminum target. Black marks indicate measurement points where this under-sampling causes uncharacteristic drops in the measured yields. These black points and other such data points were manually selected and eliminated from the reported DDTT yield measurements. The maximum kinetic energies for the DDTT light ion yields for each projectile system, after removing under-sampled points, averaged over US target thickness are presented in Table 16 in Appendix I. Light ion yields were noted up to approximate energies of 55 MeV/N to 726 MeV/N, depending upon the projectile-target dataset, angle of detection, and ion species.

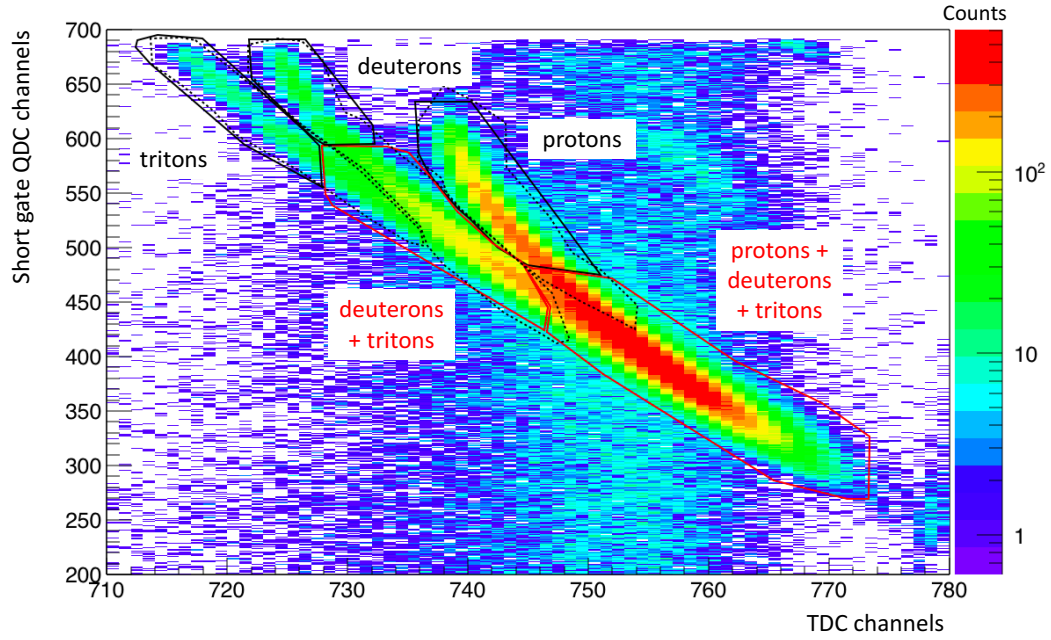


Figure 23. Light ion identification histogram for 400 MeV/N iron on all Al US targets at 10° utilizing the PSD method to isolate high energy events; featuring graphical contours used to select $Z=1$ events.

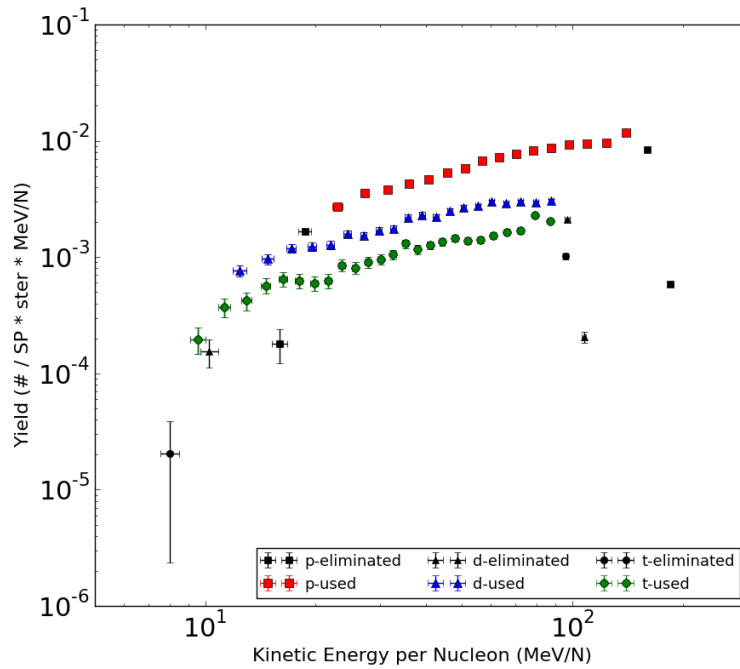


Figure 24. Experimental DDTT proton, deuteron, and triton yields for 400 MeV/N iron on 20 g/cm^2 Al US target at 10° .

V.2.2 Beam Scintillator Proton Contributions in 80° Measurements

It is likely that the plastic beam scintillators upstream from the US target contributed to proton counts measured with the 80° detector. In the particle identification histograms, a shadow feature was observed along the extent of the proton line, with a width of approximately 1.5 ns. This feature can be seen in Figure 25, which is the raw particle identification histogram at 80° for 400 MeV/N iron projectiles incident upon the three thicknesses of US target. Both the 80° and 135° OLS detector have an unblocked view of the beam scintillators, while the beam scintillators are blocked by the US target for the other four detectors. Proton events likely created by projectile interactions in the beam scintillators were also recorded in the 135° detector, but these events had TOF signatures drastically different than those produced in the US target. This difference in the TOF allowed for easy separation from US target-produced protons during the light ion identification cuts. The path length from the beam scintillator to the 80° OLS was 273.5 cm at an angle of 64°. Figure 26 is an example of a proton's total calculated TOF as a function of kinetic energy at 80°, for protons created in both the US target and the beam scintillators. The beam scintillator-generated protons have TOFs nearly identical to those produced in the US target until 100 MeV kinetic energy. At this point, the TOFs begin to differ, but they were still within ~1.0 ns until 200 MeV kinetic energy was reached.

It was not possible to subtract these events using information collected while the OLS was obscured by the shadow bar. The presence of the shadow bar alters the TDC values of any events registered during an obscured run since the TOF differs by adding up to 23 cm of steel to the flight path between the beam scintillators and the OLS. As a result, events logged during the obscured runs populate a disparate region of the light ion identification histogram when compared to events collected during un-obscured runs. Care was taken to select proton events along the line most likely correlating to US target production on the two-dimensional particle identification histogram, but it is likely the beam scintillator-produced proton events are pervasive throughout the 80° DDTT proton yield measurement results.

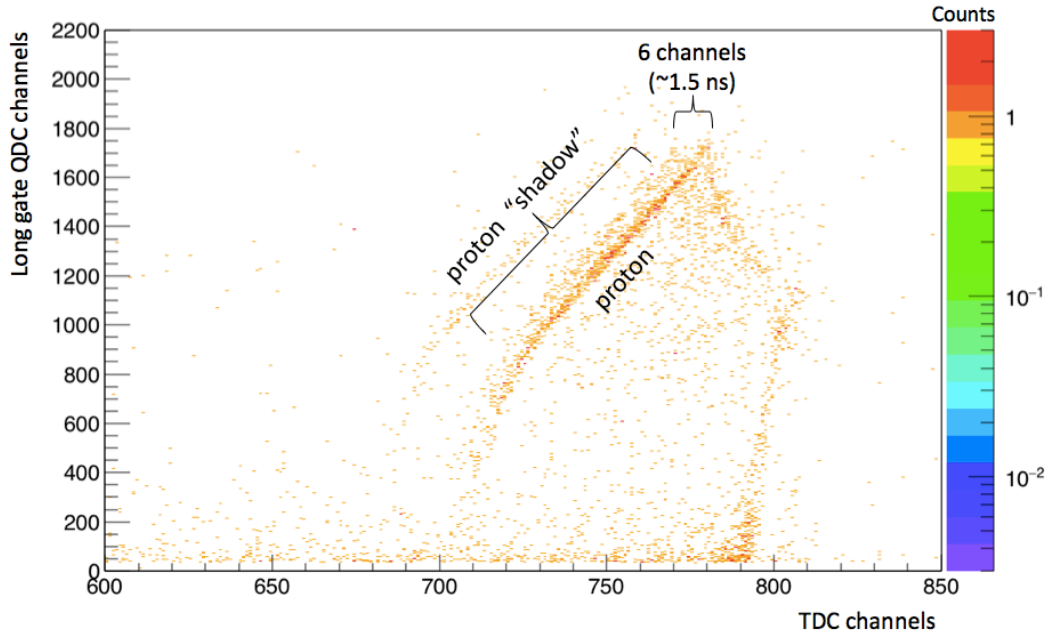


Figure 25. Light ion identification histogram for 400 MeV/N iron on all Al US targets measured at 80°.

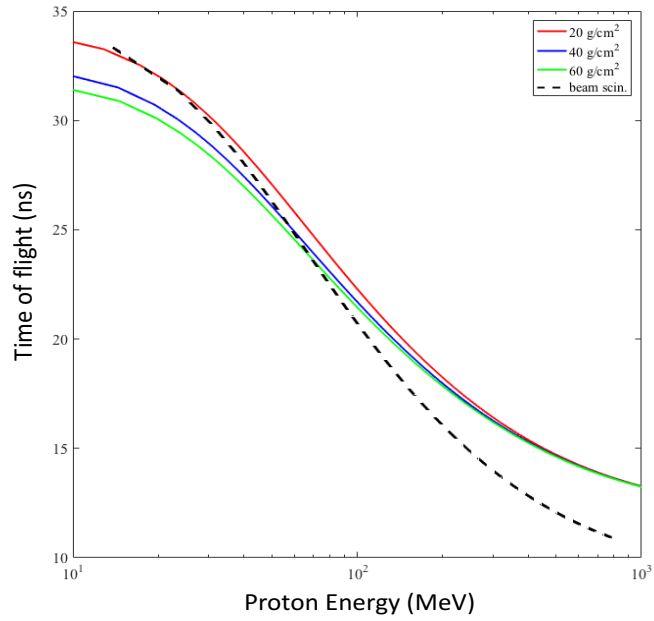


Figure 26. Proton TOF at 80° for protons produced in either the Al US target or beam scintillators.

V.3 Uncertainties

V.3.1 Overall Systematic Uncertainties

Systematic uncertainties stem from factors that influence the normalization of the thick-target yields. There were three components of systematic uncertainty considered in this analysis: solid angle, energy deposition efficiency, and ROOT graphical cuts. These three forms of systematic uncertainty were then summed to find the total systematic uncertainty for each energy bin.

Solid angle uncertainty was attributed to the uncertainty in the light ion point of production in the thick US target. Two additional points of production at the upstream and downstream surfaces of the target were assumed along with the presumed point at the center of the US target. These three production points resulted in different flight paths from the US target to the assumed point of detection. The detection point was set as the center of the active volume's surface closest to the US target. The solid angle was calculated for the three flight paths and a percent difference was found. The values used in the analysis for each US target thickness and detector position may be found in Table 10. Solid angle uncertainties ranged from approximately 0.5 to 7.8%.

The uncertainty in the energy deposition efficiency is the statistical uncertainty in the PHITS simulations described in Section IV.5. These Monte Carlo simulations estimated the fraction of light ions that deposited the maximum amount of energy in the liquid scintillator volume. The relative uncertainty in the energy deposition uncertainty for all light ions over all calculated energies was less than 0.2%.

The graphical cut uncertainty quantifies the variability in how the graphical contour cuts, which were used to select valid events, are drawn. The uncertainty in the graphical cuts is dependent upon two factors: the difference in the number of events selected in the good beam cut and the difference in the number of events selected with particle identification cuts. The fraction of live events contained within the good beam contour contributes to the final normalization of the DDTT yield spectra. The median percent difference in the fraction of events contained within the good beam contours for the six incident projectiles is shown in Table 11. Generally, this percent difference is small except for the contour used in the 800 MeV/N iron data analysis. The two contours used in this analysis are seen in Figure 27. The larger percent difference for the 800 MeV/N iron data is

Table 10. Solid angle uncertainty as function of US target thickness.

Detector	US Target Thickness (g/cm ²)		
	20	40	60
10°	2.42%	4.86%	7.30%
30°	2.13%	4.26%	6.40%
45°	1.74%	3.47%	5.21%
60°	1.47%	2.94%	4.41%
80°	0.51%	1.02%	1.54%
135°	2.60%	5.21%	7.82%

Table 11. Percent difference in GBF for each projectile species.

Projectile	Kinetic Energy (MeV/N)	Median Percent Difference between the original GBF and uncertainty GBF (%)
Fe	400	1.21
	800	13.87
He	400	1.54
	800	0.38
H	400	8.73
	800	2.87

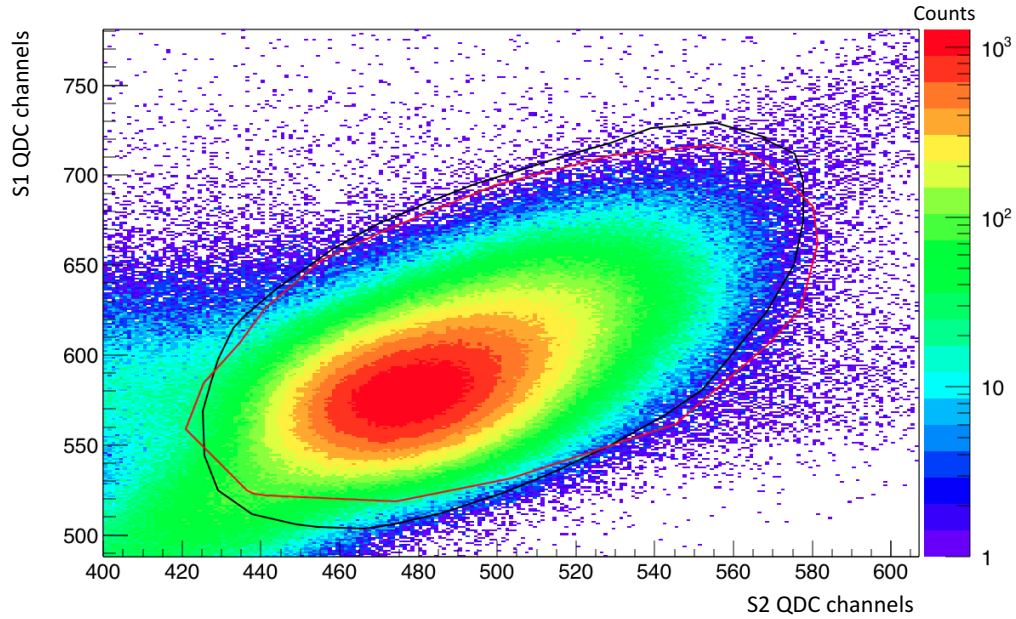


Figure 27. Beam scintillator charge collection histogram for all 800 MeV/N iron systems featuring the original (black) and uncertainty (red) good beam graphical cut contours.

likely due to the tighter uncertainty contour in the lower left-hand fragmentation feature, shown in red.

For the second contributing factor, the variance in yields due to the particle identification graphical cuts was studied by altering the contour in the highest energy region of the spectrum. The features that are used to identify individual light ions converge in the high energy region. The variance in the number of selected events due to contour cut differences in the other regions of the spectra is negligible, because clear identification of isotopes is possible. An example of the different contours used in the high energy region can be seen in Figure 23. The solid black lines are the contours used to originally select events, while the black dashed lines represent the graphical cuts used as the uncertainty set.

The analysis and normalization procedure was then performed on the two resulting sets of raw data obtained using the new set of uncertainty contours. A percent difference between the two resulting DDTT yield spectra was calculated for each projectile-target system and was subsequently used as the total graphical cut uncertainty. An example of the total graphical cut uncertainty as a function of energy is shown for hydrogen isotope ions produced by 400 MeV/N iron projectiles incident on 20 g/cm² upstream targets at 10° in Figure 28. The jump at high kinetic energies is directly attributable to the alterations in the particle identification cut where the features of the three hydrogen isotopes merge together. A summary of the median graphical cut uncertainty for each measurement set, averaged over US target thickness, is shown in Table 17 (Appendix I). The total median graphical cut uncertainties ranged from less than 1% to approximately 16%, when averaged over target thickness. In Table 17, it is evident that the relatively large uncertainties for the 800 MeV/N iron datasets are due to the large difference in the GBF noted in Table 11.

The solid angle, energy deposition efficiency, and ROOT graphical cuts uncertainties were added linearly to represent the total systematic uncertainty of a given projectile-target system. A summary of the total median systematic uncertainty for each measurement set, averaged over US target thickness, is shown in Table 18 (Appendix I). The total median systematic uncertainties ranged from approximately 2 to 21%, when averaged over target thickness.

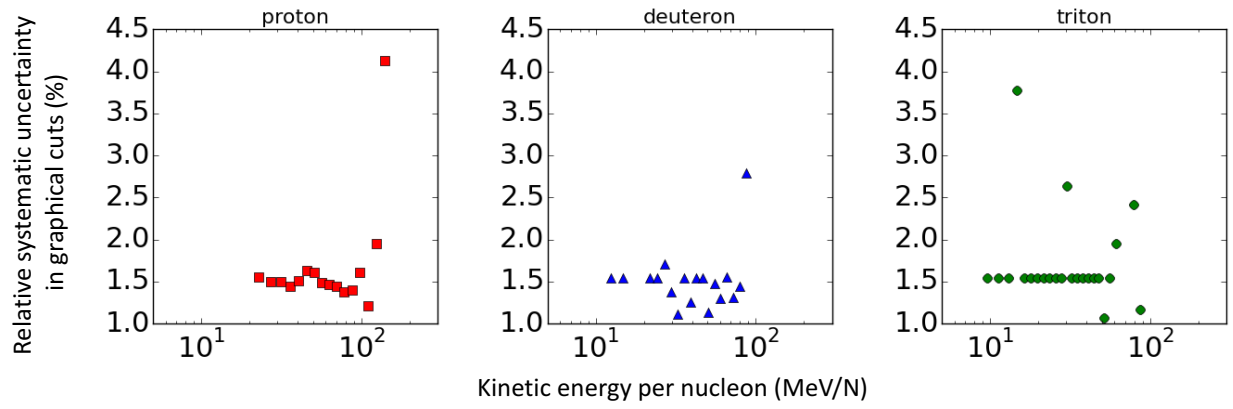


Figure 28. Relative systematic uncertainties due to graphical cuts for DDTT hydrogen isotope yields; 400 MeV/N iron incident on 20 g/cm^2 Al US targets at 10° .

V.3.2 Overall Statistical Uncertainties

Statistical uncertainty varied greatly over all the light ion types. For the measurements with best counting statistics, i.e. the measurements from the three most forward-focused detectors, the statistical uncertainty typically decreased as a function of the measured kinetic energy of the light ions. The median uncertainties for these detectors were less than 10% relative uncertainty for protons, less than 30% for deuterons, and less than 60% for tritons. For the helium isotopes, the 10° detector had the best counting statistics. Median statistical uncertainties were less than 10% for the iron projectile data, with more variance noted for the helium projectile data. A summary of the median statistical uncertainties for each measurement, averaged over US target thickness, is shown in Table 19 (Appendix I).

A summary of the median statistical uncertainties for the MCNP-LAQGSM simulated yields, averaged over US target thickness, is shown in Table 20 (Appendix I). The counting statistics for the simulated yields were poor at angles greater than 45° for secondary protons. The median relative statistical uncertainties in the MCNP-simulated DDTT proton yields were below 32% for forward angles (10° to 45°) for all projectiles studied. The relative median statistical uncertainties for the $A > 1$ light ions were generally poor for all detection angles except at 10°. Here, iron projectiles produced favorable counting statistics for all light ions (~20% relative uncertainties), but helium projectiles only had similar favorable uncertainties for deuterons. The median uncertainties for deuterons produced by hydrogen projectiles were 30% or greater for all detection positions. It is important to note that the dynamic range of the simulations is much greater than that for the experimentally-measured DDTT yields, ranging from 10 MeV/N to the projectile energy, and statistical uncertainties may vary greatly with the kinetic energy of the fragment. Because of the variance in the statistical uncertainties over a wide range of simulated energies, the median values reported in Table 20 may be skewed higher than what was observed in the energy region that overlapped the experimental measurements.

V.3.3 Energy Uncertainties

Uncertainty in the kinetic energy of the measured light ions arises during the TOF-to-energy conversion. Since the exact production point of light ions in the US target is unknown in the experiment, three production point positions within the US target are assumed: the upstream face, the center, and the downstream face. Once again, the detection point in the liquid scintillators is set at the center of the circular surface of active volume closest to the US target. TOF-to-kinetic energy conversion tables were generated for each of these production points using the methodology detailed in Section IV.4.2. Light ions generated at these production points take different flight paths during transit from the US target to the detector, and as a result, pass through differing amounts of US target material. An illustration of the proton TOF-to-energy conversion data for the three different production points in each Al US target thickness at 10° is shown in Figure 29. The space between the red, blue, and green lines demonstrate the difference in calculated kinetic energies at a given TOF. This difference increases with decreasing TOF and is most noticeable as the Al US target thickness is increased. These calculated differences in kinetic energy are the basis for the energy bin uncertainties.

The uncertainty in energy for DDTT light ion yields is calculated by converting the TOF axis from channels to ns for each production point. This calibration was achieved using the prompt gamma ray TOFs calculated with the same three production points stated above. These TOF axes are then converted to energy using the TOF-to-kinetic energy data set corresponding to the US target thickness, detector angle, light ion species, and the assigned production point. The TOF values corresponding to production in the center of the US target is taken as the “true” TOF axis, while the remaining two TOF datasets were used to calculate the energy uncertainty. Because our collaborators requested symmetric energy uncertainties, the two remaining sets of TOF values were averaged in quadrature to calculate an energy uncertainty per bin. An example of the energy uncertainties for proton measurements are presented in Figure 30 for the bombardment of 400 MeV/N iron projectiles on aluminum targets at 10° . The aforementioned increase in energy uncertainty with increasing kinetic energy (and decreasing TOF) is easily seen here. As previously mentioned, the measured DDTT yields presented in this work are displayed with the horizontal energy uncertainties. More often than not, they are small and not visible behind the plot markers.

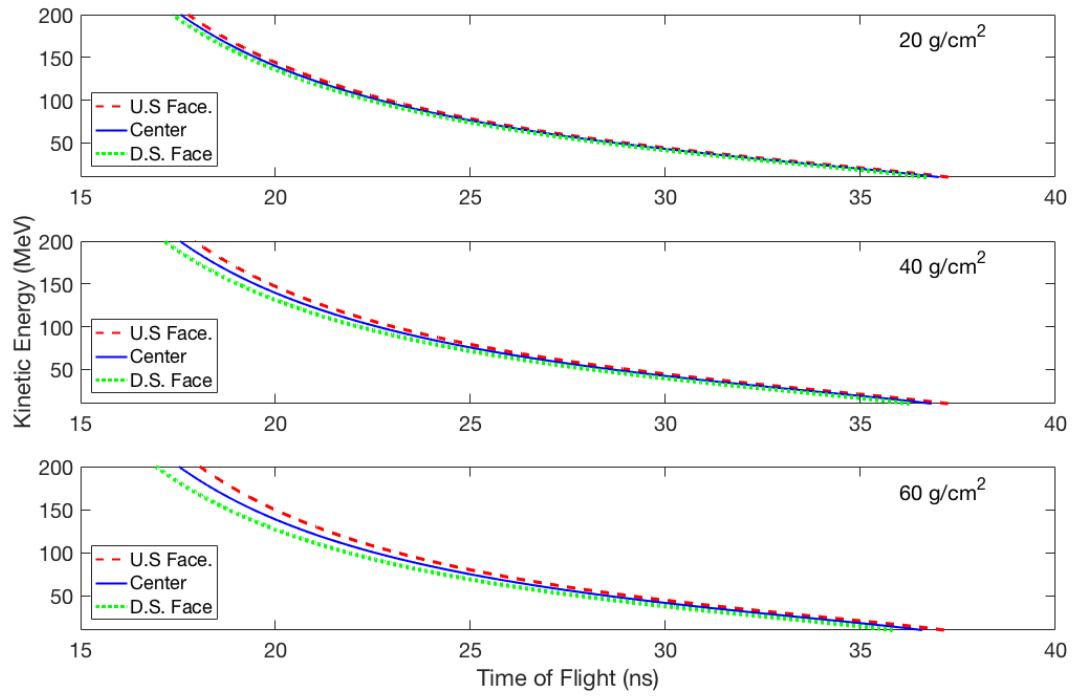


Figure 29. TOF to energy conversion data for protons from Al US targets at 10°.

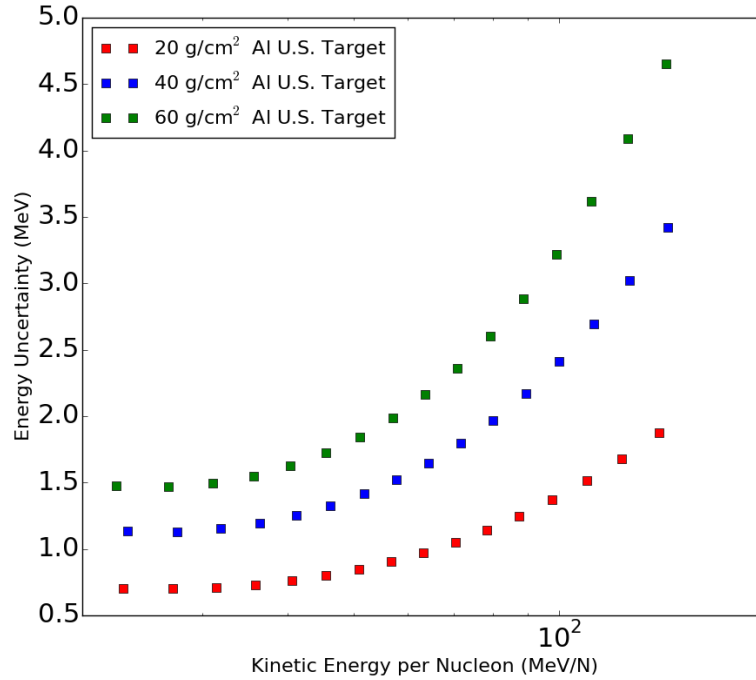


Figure 30. Uncertainty in kinetic energy based on differing production points for protons from Al US targets at 10°.

V.4 Comparisons Between Measured Data and MCNP-LAQGSM Simulations

V.4.1 *Iron Projectiles*

V.4.1.1 DDTT Hydrogen Isotope Yields

DDTT hydrogen isotope yield data for iron projectiles are shown in Figure 35 through Figure 46 in Appendix II. The proton measurements are generally matched well by the simulation results for both 400 and 800 MeV/N iron projectiles. Typically, the agreement between the simulations and measurements improve with an increase in target thickness, as well as with an increase in detection angle. The most interesting disagreement occurs at the 10° detector. Here, the simulation agrees better with the measurements for the 800 MeV/N projectile data, whereas the simulations under-predict the measurements for the 400 MeV/N projectile energy which generates a flatter spectrum. The disagreement between the simulated and measured yields at 10° for the 400 MeV/N projectiles is reduced with an increase in US target thickness.

For deuterons, the simulations generally agree well with the measurements for the three forward detectors (10° to 45°) for both projectile energies. At wider angles, the simulation has difficulty producing deuterons at the widest detection angles for each projectile energy (80° for 800 MeV/N iron and 60° for 400 MeV/N iron) with the 40 and 60 g/cm² aluminum US targets.

The simulated triton yields disagree with the measurements for the 10° detector with the 400 and 800 MeV/N iron projectiles. Generally, the shape of the spectrum is reproduced by the simulation, but there is an approximate factor of two difference in magnitude between the simulated and measured yields. The difference between simulated and measured yields generally decreases as the US target thickness increases. For the measurements with the 800 MeV/N iron projectiles incident on 20 g/cm² aluminum at 10°, MCNP predicts a sharper peak around the incident projectile energy than what was observed. Additionally, the simulations produce higher triton yields at the lower end of the measureable energy range with subsequent increases in US target thickness. By contrast, the measured yields suggest the spectral shape is more consistent across the three US target thickness results, whereas the simulations only reproduce the spectral shape for the 40 and 60 g/cm² US target results. The simulation agrees with the measured results between

30° and 60°, except at the respective widest position measurements (60° for 800 MeV/N iron and 45° for 400 MeV/N iron) for the 40 and 60 g/cm² US targets.

V.4.1.2 DDTT Helium Isotope Yields

DDTT helium isotope yield data for iron projectiles are shown in Figure 71 through Figure 74 in Appendix II. Simulation results for the iron-produced helium-3 ions generally agree with the measured helium-3 yields in both spectral shape and magnitude. Points of disagreement again arise with the 20 g/cm² measurements at 10° for both 400 and 800 MeV/N iron projectiles. There is approximately a factor of two difference in the DDTT yield magnitude, but the shape of the spectrum is generally replicated by the simulation for these data sets. This disagreement disappears in the thicker US target spectra. At the 30° position, little to no helium-3 is produced by the simulations for 400 MeV/N iron projectiles incident on 40 and 60 g/cm² US targets. Conversely, helium-3 ions over a range of kinetic energies were measured during the experiment. The 800 MeV/N iron projectile simulations did predict helium-3 yields that were similar to the measured yields with all three US target thicknesses at 30°.

At 10°, helium-4 ion yields produced by the simulations seem to agree in spectral shape, but all disagree in magnitude. These trends are observed across the three US target thicknesses. Interestingly, the simulation predicts that the helium-3 and helium-4 yields are almost identical in shape and magnitude, which was not evident in the measured data outside of the 800 MeV/N iron on 20 g/cm² US target system. Here, the measured helium-3 and helium-4 yields followed this trend, though the measured yields were larger than what is predicted by the MCNP simulation. At 30°, only the 800 MeV/N iron projectiles produced viable helium-4 measurements during the experiment. The 800 MeV/N iron simulation produced few helium-4 ions with highly varying yields for the 40 and 60 g/cm² US targets.

V.4.2 Helium Projectiles

V.4.2.1 DDTT Hydrogen Isotope Yields

DDTT hydrogen isotope yield data for helium projectiles are shown in Figure 47 through Figure 58 in Appendix II. Simulated proton yields agree fairly well with the proton measurements for the 800 MeV/N helium projectile data. However, there is disagreement between the experimental values and the calculated values for 400 MeV/N projectile data at 10° and 30°. Similar to the iron projectile data, the simulations for these datasets under-predict the proton yields. The measurements suggest a less rapid drop in yield as the kinetic energy decreases. Interestingly this feature is also noticed at 30°, which was not observed with the iron projectile data. The larger angle proton yields for 400 MeV/N helium projectiles are well-represented by the simulation.

The 800 MeV/N helium projectile simulations provide suitable agreement for deuterons at all detection angles. The 400 MeV/N helium projectile measurements largely disagree with the simulated yields, with the simulated yields under-predicting the measurement by nearly a factor of five at 10°, and a factor of three at 30°. Despite the difference in magnitudes, the measured and simulated spectra both displayed a similarly flat shape in yields. At 45°, the simulations and measurements only agree with the 60 g/cm² US target, while at 60°, the simulations and measurements agree across all target thicknesses.

The triton measurements from 400 MeV/N helium at 10° are not well-predicted by the simulation. The simulation yield spectra have a large drop at 30 MeV/N kinetic energy that is not observed in the measured spectra. At wider angles, the simulations loosely resemble the measured results. For the 800 MeV/N projectile data, the measured triton results were well-represented by the simulated quantities at 10° and 30°.

V.4.2.2 DDTT Helium Isotope Yields

DDTT helium isotope yield data for helium projectiles are shown in Figure 75 through Figure 78 in Appendix II. The simulations for 400 MeV/N helium projectiles do not produce helium isotope yield spectra consistent with the recorded measurements. The simulated helium-3 yields at 10° are

barely produced with the 20 and 40 g/cm² US target. With the 60 g/cm² US target, the simulation under-predicts the measured yields by more than an order of magnitude. For helium-3 at 30°, the simulation produces highly varying yields with large statistical uncertainties. These simulated yields are on the same order of magnitude as the measured results. Similarly, the measured helium-3 yields for the 800 MeV/N helium projectiles are similar in magnitude to the simulations at both the 10° and 30° detection positions, though the simulated yields are highly varying with large uncertainties.

Additionally, the MCNP simulations for the 400 MeV/N helium projectiles do not predict helium-4 ion detection with any target thickness at 10° or 30°, although yields were measured experimentally at these positions. For the 800 MeV/N helium projectiles, valid measurements were only collected at 10° and 30° with the 20 g/cm² US target. These results are not displayed in Appendix II, and are instead discussed in Section V.5.5.

V.4.3 Proton Projectiles

V.4.3.1 DDTT Hydrogen Isotope Yields

DDTT hydrogen isotope yield data for proton projectiles are shown in Figure 59 through Figure 70 in Appendix II. Much like the results produced by the heavier projectiles, the simulations are successful at predicting the proton yields measured at all angles with the 800 MeV proton projectile systems. Similar to the heavy projectile results, the MCNP simulation for the 400 MeV/N proton projectiles predicts a more rapid decline in proton yields at 10° and 30° as the kinetic energy decreases, when compared to the measured yields. Measurements at 10° suggest a buildup of protons around 80 MeV kinetic energy for all US target thicknesses. Measured yields are under-predicted by the simulated yields across the full detected energy range. The measurements for the 400 MeV/N proton projectiles at 30° showcase the most uncommon data trend from the whole experiment: the 30° yields are higher than the 10° yields, which is also predicted by the MCNP simulation. The simulated yields with the 20 g/cm² US target fall off much more rapidly as the kinetic energy decreases when compared to the measured yields, and the peak near the incident projectile energy is less broad than what is suggested by the measurement. The shape of the

measured spectra is better represented by the simulations for the 40 g/cm² and 60 g/cm² US targets, with the 40 g/cm² simulated spectra slightly under-predicting the proton kinetic energies below the peak. The simulated yields provide good agreement with the measured yields between 45° and 135°.

For the 800 MeV projectile data, simulated and measured yields agree well for deuterons between 10° and 60°. For 400 MeV proton projectiles, there is disagreement between the two for the deuteron yields at the 10° and 30° positions, similar to what was seen with the proton yields. At both angles, the simulated quantities demonstrate a reduction in yield over all kinetic energies as the US target thickness increases, but the measurements suggest that the deuteron yields are generally constant in magnitude as the target thickness increases. The simulation and measurement roughly agree at 45°.

V.5 Comparisons Between Measured Data and Monte Carlo Physics Model Calculations

V.5.1 DDTT Proton Yields for Iron and Helium Projectiles

Comparisons to DDTT proton yield data are shown in Figure 79 through Figure 84 in Appendix III. Generally, there are minor differences between the simulation results and proton measurements for incident 800 MeV/N iron and helium projectiles in the measureable kinetic energy range. For the incident 800 MeV/N iron projectiles, the two MCNP model results (LAQGSM and ISABEL) are nearly identical for proton yields. This is because the incident iron projectile interactions are handled by LAQGSM regardless of the physics model selected by the user [30]. Similarly, proton secondaries are all handled by CEM, regardless of user selection. The PHITS-calculated proton yields for the 800 MeV/N iron projectiles are similar to the yields generated with the LAQGSM and ISABEL MCNP physics models. Slight differences between PHITS and MCNP occur at 10° and 30°, where the magnitude of the measured yields is more closely modeled by the PHITS results versus the MCNP results at the high end of the kinetic energy range above 100 MeV. It should be noted that at all angles, PHITS generates flatter proton spectra at low energies which is not reflected in the measurements. In this energy region, the LAQGSM and ISABEL MCNP models more accurately predict the measurement results.

For protons produced by 800 MeV/N helium projectiles, the three physics models again produce largely the same results, which generally reflect the measurement yields between 10° and 80°. Areas of disagreement include the afore-mentioned over-prediction of proton yields by PHITS at low energies, as well as the following differences between the simulated and measured results at 135°. Here, The ISABEL and PHITS results are nearly identical to each other and to the measurement results, while the LAQGSM results are nearly a factor of two lower. Despite being outside of the measureable energy range, the trend noted between the ISABEL, PHITS, and LAQGSM simulations was also observed at the projectile peak in the 10° spectra.

For 400 MeV/N iron and helium projectiles, the largest differences were noted at the forward-most detectors at 10° and 30°. The ISABEL and LAQGSM MCNP-simulated yields for the 400 MeV/N iron projectile-produced protons are nearly identical to each other as previously noted. Both MCNP physics models underestimate the proton yields in the measured energy range at 10°. The PHITS-produced spectrum is identical in shape to the two MCNP spectra, but the yields at lower energies are nearly 50% greater than the MCNP-produced yields. MCNP and PHITS results begin to agree with each other past the projectile peak kinetic energy at 10°. Throughout the measureable energy range, the experimental yields basically split the difference between the MCNP- and PHITS-calculated yields. At 30°, the three physics models more closely agree with each other and the measurements. Between 45° and 135°, the three physics model simulations all provide reasonable agreement with the measured yields.

For the 400 MeV/N helium projectile system, the ISABEL physics model in MCNP most closely reflects the proton yield measurements at 10°. For 400 MeV/N helium projectiles at 30°, the three physics models under-predict the measurement yields, but the PHITS and ISABEL results are marginally closer to the measurements than the LAQGSM results. Once again, the three physics model simulations all provide reasonable agreement with the measured yields between 45° and 135°.

V.5.2 DDTT Deuteron Yields for Iron and Helium Projectiles

Comparisons to DDTT deuteron yield data are shown in Figure 85 through Figure 88 in Appendix III. The physics model results vary the most with the production of light ions with $A > 1$. As seen with the proton yields, both LAQGSM and ISABEL physics models produce nearly identical deuteron results for the iron projectiles. At 10° and 30° , the 800 MeV/N iron-produced deuteron yields are slightly under-predicted by MCNP's LAQGSM and ISABEL, and the deuteron yields are more severely under-predicted by PHITS. At 30° , the shape of the measured spectrum is matched more closely by PHITS, despite the difference in overall magnitude. For the 800 MeV/N iron-produced deuteron measurements at 45° and 60° , the three physics model results overlap with each other in the measureable kinetic energy region and generally agree with the deuteron measurements. For 800 MeV/N helium-produced deuterons, the PHITS and LAQGSM MCNP results represent the upper and lower bounds, respectively, for the measured yields between 10° and 60° . In this energy region, ISABEL greatly under-predicts the measurements. Outside of the measureable range, ISABEL predicts a peak around the projectile energy at 10° , while LAQGSM and PHITS do not predict such a feature.

Measured deuterons generated by the 400 MeV/N iron projectiles at 10° are most closely matched by both LAQGSM and ISABEL, which slightly under-predict the experimental yields. The PHITS results are nearly identical to the MCNP results below kinetic energies of 30 MeV/N. PHITS and MCNP results diverge above 30 MeV/N, with PHITS generating a broader peak at the projectile energy with a lower yield magnitude. The measured deuteron yields at 30° are under-produced by the three physics models, while this disagreement lessens as the detection angle is increased. For 400 MeV/N helium projectiles, the measured deuteron yields are well-represented by PHITS between 10° and 60° . The LAQGSM results approximate the shape of the measurements, but the yield magnitudes are nearly a factor of two lower than the measured yields. The ISABEL-calculated deuteron yields are lower than the LAQGSM yields at each detection angle, differing by an order of magnitude from the measurements at 10° . The difference between the ISABEL and measured yields decrease as the detection angle increases, differing by up to a factor of 5 at 60° . As previously seen with the 800 MeV/N helium projectile simulations at 10° , ISBAEL generates

a peak near the projectile energy for deuterons produced by 400 MeV/N helium. This trend is not corroborated by the PHITS and LAQGSM physics model simulations.

V.5.3 DDTT Triton Yields for Iron and Helium Projectiles

Comparisons to DDTT triton yield data are shown in Figure 89 through Figure 91 in Appendix III. Trends between the triton measurements and simulations are similar to the trends noted for the deuterons. LAQGSM and ISABEL simulations slightly under-predict the triton yields for 800 MeV/N iron projectiles at 10°, with the MCNP simulations approaching the measurement results as the angle of detection increased. PHITS generally produces lower tritons yields than the MCNP physics models for the 800 MeV/N iron projectiles, with PHITS also predicting a steeper yield decrease as the kinetic energy of the tritons increase at all angles. For 800 MeV/N helium-produced tritons, the LAQGSM and PHITS models produce results that are generally consistent with one another, although there are slight differences in their yield magnitudes. These two sets of results generally provide an upper (PHITS) and lower (LAQGSM) bound on the measured data. ISABEL produces highly varying triton yields that do not agree with the other simulations for the 800 MeV/N helium system.

Tritons produced by 400 MeV/N iron reactions measured at 10° are unpredicted by all three physics models. The LAQGSM and ISABEL MCNP simulations are most consistent with the shape of the measured triton yield spectrum, though MCNP underestimates the measured yields by nearly a factor of two. The PHITS results are generally identical to the MCNP results below 30 MeV/N, but diverge at higher energies, predicting a shallower peak at the incident projectile energy outside of the measurable energy range. The relation between the simulated and measured yields at 30° and 45° are generally the same: LAQGSM most closely resembles the measurements below 30 MeV/N, while PHITS and ISABEL under-represent the measurements by nearly an order of magnitude below 30 MeV/N. Above 30 MeV/N kinetic energy, the two MCNP simulations are identical, but they are below the measured yields. The differences seen between PHITS and the MCNP results at 30° and 45° are more pronounced than at 10°.

For the 400 MeV/N helium-generated tritons, the measurements are well-predicted by PHITS across all kinetic energies at 10°. The LAQGSM results roughly agree with the measurements below 30 MeV/N kinetic energy, while ISABEL again under-predicts the measurements. ISABEL also produces a sharp peak around 350 MeV/N, which is the kinetic energy of the projectile as it exits the US target. This peak is not predicted by the physics models, much like the 800 MeV/N helium projectile results for tritons. At 30° and 45°, LAQGSM and PHITS agree with the measurements below 30 MeV/N, while they over- (PHITS) and under- (LAQGSM) predict the measurements at higher kinetic energies. Contrastingly, ISABEL simulations of 400 MeV/N helium basically do not produce tritons at these angles.

V.5.4 DDTT Helium-3 Yields for Iron and Helium Projectiles

Comparisons to DDTT helium-3 yield data are shown in Figure 92 and Figure 93 in Appendix III. The physics models considered in this work demonstrate the same general capabilities and trends when producing helium isotopes, as was seen with the hydrogen isotopes. For 800 MeV/N iron-produced helium-3 fragments at 10°, the nearly identical LAQGSM and ISABEL MCNP results replicated the shape of the measurement yields but underestimate their magnitudes. The PHITS results also reproduce the shape of the measurements, but are more than an order magnitude lower than the measured yields. At 30°, the generally flat shape of the measured yields is reproduced by MCNP, though the simulations are lower in magnitude. The PHITS results do not reflect the shape or magnitude of the measurements at 30°.

The 800 MeV/N helium projectile-produced helium-3 fragments are closely predicted by PHITS at 10°. The magnitudes of these measurements are under-predicted by LAQGSM, though the shape is well-reproduced in the simulations. The ISABEL results are not consistent with the measurements and form a noisy, highly varying peak at the projectile kinetic energy at 10°, which is outside of the measurable energy range and is not predicted by the other physics models. At 30°, the measurements are again best matched by PHITS. ISABEL produces little to no helium-3 fragments at this position, while LAQGSM under-predicts the measurements though the spectral shape is generally consistent.

Trends noted for the 800 MeV/N iron- and helium-produced helium-3 ions were also noted with the 400 MeV/N iron and helium projectiles. At 10°, the magnitude of the helium-3 measurements for the 400 MeV/N iron projectile system are under-predicted but matched in shape by the identical MCNP model results. These measurement yields were once again severely underestimated by PHITS, though the spectral shape was well-modeled. At 30° the MCNP results more closely approximate the magnitude and spectral shape of the measured helium-3 yields, while PHITS under-predicts the measurements by an approximate order of magnitude. For the 400 MeV/N helium projectile system, the helium-3 measurements are best replicated by PHITS at 10°, while LAQGSM and PHITS provide a lower and upper bound, respectively, of the results at 30°. ISABEL is lower than the measured helium-3 yields at 10° and once again produces the incident projectile peak not seen by the other physics models. ISABEL simulations for 400 MeV/N helium projectiles do not predict the measurement of any helium-3 fragments at 30°.

V.5.5 DDTT Helium-4 Yields for Iron and Helium Projectiles

Comparisons to DDTT helium-4 yield data are shown in Figure 94 and Figure 95 in Appendix III. Helium-4 fragments produced by iron projectiles at 400 and 800 MeV/N follow the same trends seen with the helium-3 fragments. For 800 MeV/N iron projectiles at 10°, the LAQGSM and ISABEL MCNP results approximate the shape of the measured spectrum well, but are nearly a factor of four below the measured yields. For 400 MeV/N iron projectiles at 10°, the PHITS-simulated helium-4 results are most consistent with the MCNP simulations when compared to the other $A > 1$ light ion fragments. However, these PHITS and MCNP results are still nearly an order of magnitude below the helium-4 measurements. At 30°, the measured yields are a factor of 2 higher than the MCNP-produced results for both 400 and 800 MeV/N iron projectiles, though the spectral shape of the helium-4 yields is generally consistent. PHITS results at 30° underestimate the measured yields by up to an order of magnitude.

The helium-4 yields for the 400 and 800 MeV/N helium projectile systems represent a unique scenario for the Monte Carlo simulations. Here, the incident projectile particle is also the

secondary particle counted in the detector. Different physics models are used by the Monte Carlo transport codes used in this work to transport heavy ions and nucleons. Thus, the simulated helium-4 yields represent the ability of the physics models to scatter nuclei in thick targets, where the likelihood of multiple interactions is high. This is of great importance when modeling radiation exposures in space environments, since helium-4 particles are the second most abundant constituent of GCR. As seen in the results, the two MCNP physics models largely do not have the capability to predict helium-4 yields for incident 800 MeV/N and 400 MeV/N helium-4 projectiles at either 10° or 30°. On the other hand, PHITS effectively predicts the spectral shape and magnitude of the measured helium-4 spectra.

V.6 Discussion

The protons yields are generally well-represented by simulations of all incident projectiles, except at 10° and 30° for projectiles at 400 MeV/N striking the 20 g/cm² Al US target. For these datasets, the simulations underestimate the proton yields with high kinetic energies. This difference between the simulated and measured yields is reduced as the US target thickness is increased. A cause for the disparity are the contributions from particles produced in the back target or in the air column along the beam axis. Evidence of the particles not being produced in the US target can be seen on the light ion identification histograms for 800 and 400 MeV/N iron projectiles on Al US targets at 10° in Figure 31. These extraneous particles are contained within the green and blue patches of uncorrelated events seen behind the lines associated with light ions originating in the US target. The extent of these regions is further indicated with the black arrows. The high-count region of uncorrelated events is wider as a function of TOF for the 400 MeV/N projectiles than it is for the 800 MeV/N projectiles. More importantly, the high-count regions for 400 MeV/N projectiles pervade into the areas of the histogram where light ion events consistent with US target production are present.

To better enumerate the characteristics of these uncorrelated patches of events, recall the prompt gammas TOF is ~13 ns (~10 ns to travel from the US target to the detector as shown in Table 8, and ~3 ns for the incident projectile to travel between the beam scintillator and the target). The

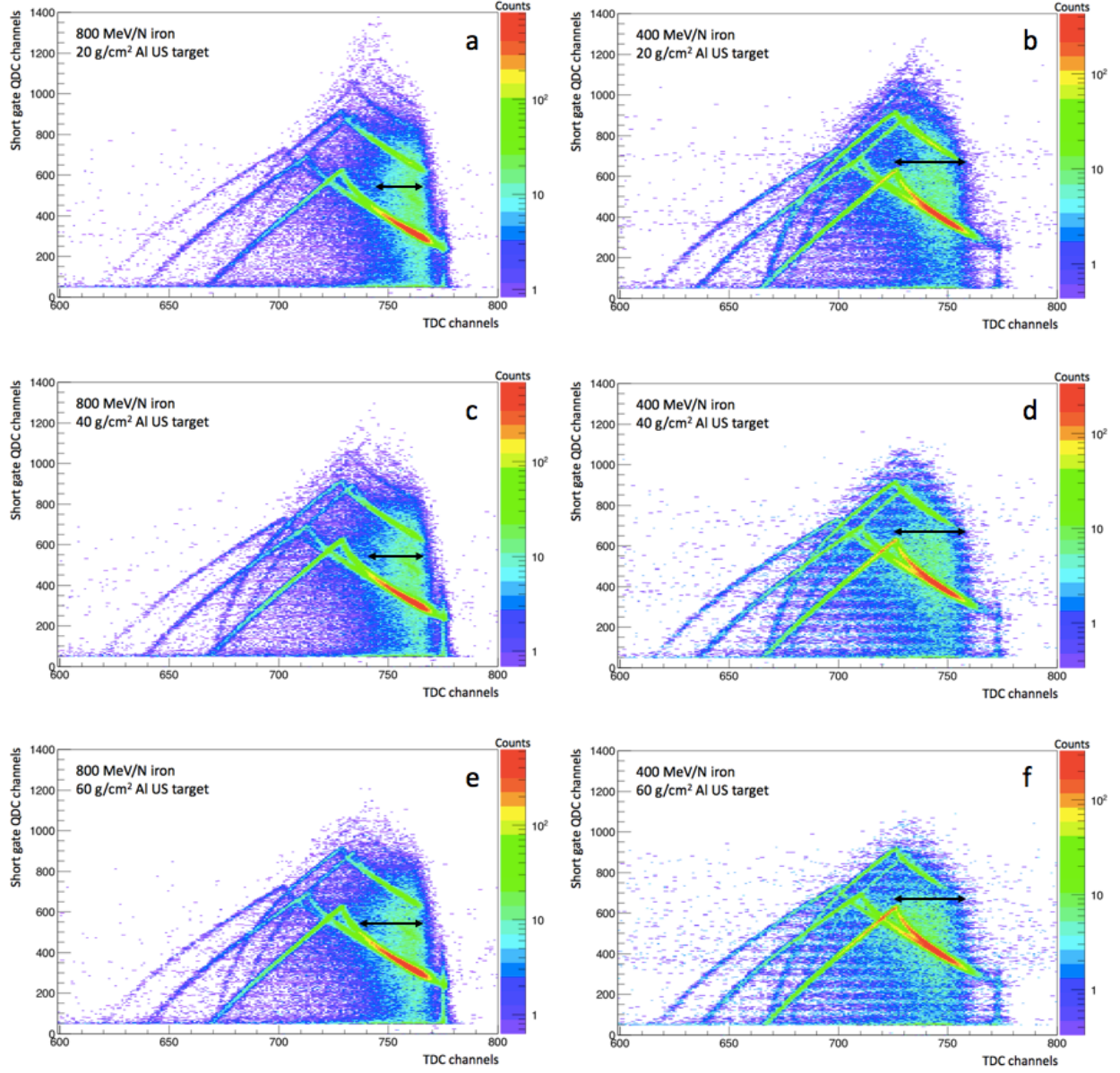


Figure 31. Light ion identification histograms for 800 MeV/N (left) and 400 MeV/N (right) iron projectiles on 20 (a-b), 40 (c-d), and 60 (e-f) g/cm² Al US targets at 10°.

TOF of the punch-through-protons in the 10° detector is ~ 24 ns (values in Table 7, plus the aforementioned ~ 3 ns for the incident projectile). Calculated TOFs for protons produced at various positions in the air column between the US and DS target as a function of proton kinetic energy at OLS entrance are presented in Figure 32. The TOFs of these air column-produced protons fit the range of TOFs exhibited by the uncorrelated event patches seen on the right side of Figure 31. The TOF of particles produced in the DS target is more difficult assess, since the points of production leading to the creation of any further secondaries would be less certain. At the least, an incident projectile beginning with 400 MeV/N would take 20.1 to 22.3 ns to propagate un-collided from the beam scintillators, through the US target, and to the surface of the DS target. Note that particles incident on the OLS with origins besides the US target would impinge on the OLS differently than anticipated, making energy deposition higher than the previously reported punch-through kinetic energies possible; the maximum such amount would be 148 MeV in EJ-301.

It was not possible to remove the contributions of extraneous detection events by utilizing background subtraction methods. Background subtraction would require using events detected while the OLS array was obscured with the shadow bar, constituting a background spectrum. For further comparison to be shown here, covered detector events were selected with the previously mentioned particle identification graphical cuts. The background events were then processed with the same time-walk correction procedure and normalized to live time and number of source particles. An example of the TDC spectrum of shadowed events and uncovered proton detection events recorded with the 10° OLS detector during the 400 MeV/N iron projectile bombardments of $20 \text{ g/cm}^2\text{Al}$ US target is shown in Figure 33. The spectrum of events collected during the shadowed runs are generally two orders of magnitude less than the uncovered DDTT proton yield events, and would not significantly affect the magnitude of the measured yields if background subtraction were applied.

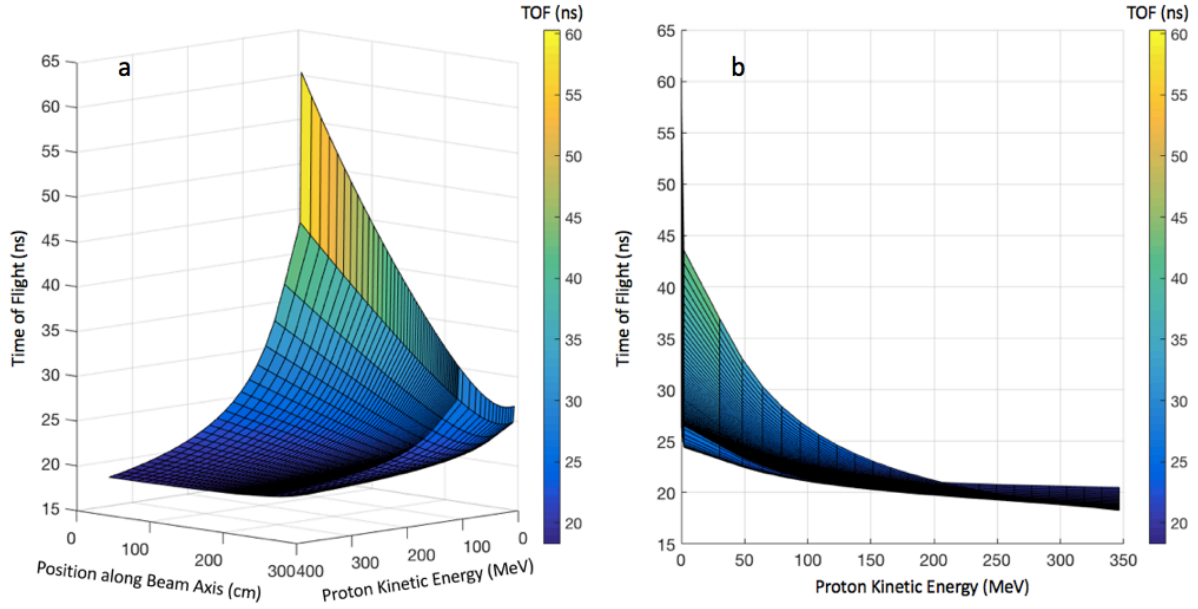


Figure 32. Calculated TOF of protons produced in the air column along the beam axis for 400 MeV/N incident projectiles emerging from 20 g/cm² Al US target at 10°. (a) As a function of starting position along beam axis between US and DS targets. (b) Rotated to view proton kinetic energy and TOF axis view only.

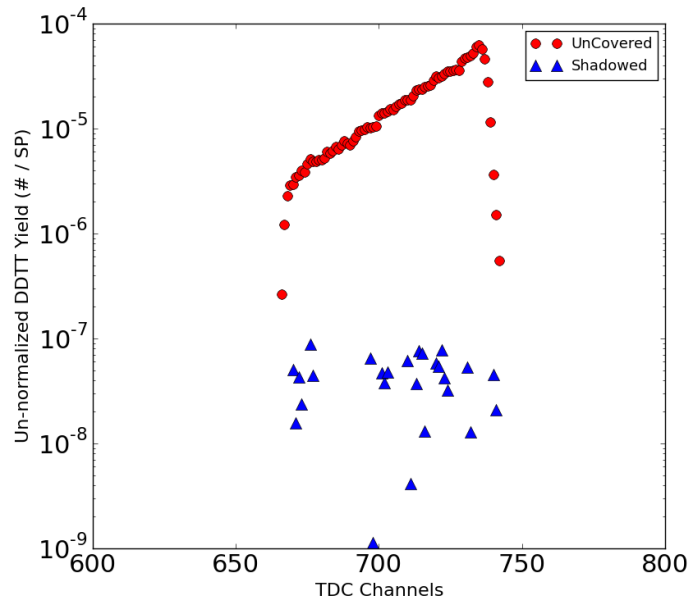


Figure 33. Measured TDC spectrum collected during covered and uncovered runs corresponding to protons for 400 MeV/N iron projectiles on 20 g/cm² Al US targets at 10°.

Each OLS array was outfit with two plastic scintillator paddles to serve as veto detectors, as mentioned in Section IV.1.4.2. While one was placed directly in front of the OLS to discriminate charged and neutral particle events, the other was placed on the side and oriented to face the beam axis air column. Isolating events depositing energy in this latter veto paddle proved to represent events where there was a detection event in the OLS which was consistent with US target production by following the energy deposition signatures on the light ion identification histogram detailed in Section IV.3.2. In conjunction with these correlated events, an anomalous event additionally deposited energy in the secondary veto paddle. There was no further mechanism to separate these detection events from each other.

Cascade-model event generators used in Monte Carlo transport codes are based on assumptions relating the space between interaction sites and the interaction time to the de Broglie wavelength of the incident particle [41]. This assumption becomes tenuous at the high end the measurable-energy range (100 to 200 MeV) of the OLS where multiple light ions are incident. Given the presence of anomalous detection events, and the fact that thick-target measurements are inherently sampling many interaction types occurring at many kinetic energies [42], it is difficult to pin the cause of the disagreement between the measured and simulated DDTT yields of protons at forward directions (10° to 30°) on any one factor.

It is worthwhile to revisit the way the MCNP simulation results were calculated as detailed in Section IV.6. The simulated particle tracks that were scored in the tally had a restriction on the cosine of the particle track with respect to the tallying surface, the quantity k . The effect of this restriction can be seen in the comparison of measured and simulated DDTT proton yields from 800 and 400 MeV/N iron projectiles on 20 g/cm^2 Al US targets at 10° shown Figure 34. For the 800 MeV/N projectile, the cosine restriction is successful in replicating the measured quantity. For the 400 MeV/N projectile system, the measured spectrum is best replicated by the simulation that includes all proton tracks. The cosine restriction is successful in eliminating particle tracks originating from sources outside of the US target in the simulated DDTT yields. However, the contributions of these extraneous particles may not be eliminated from the measured yields at 10° and 30° . This is less of an issue at 800 MeV/N since the source term of extraneous particles is not

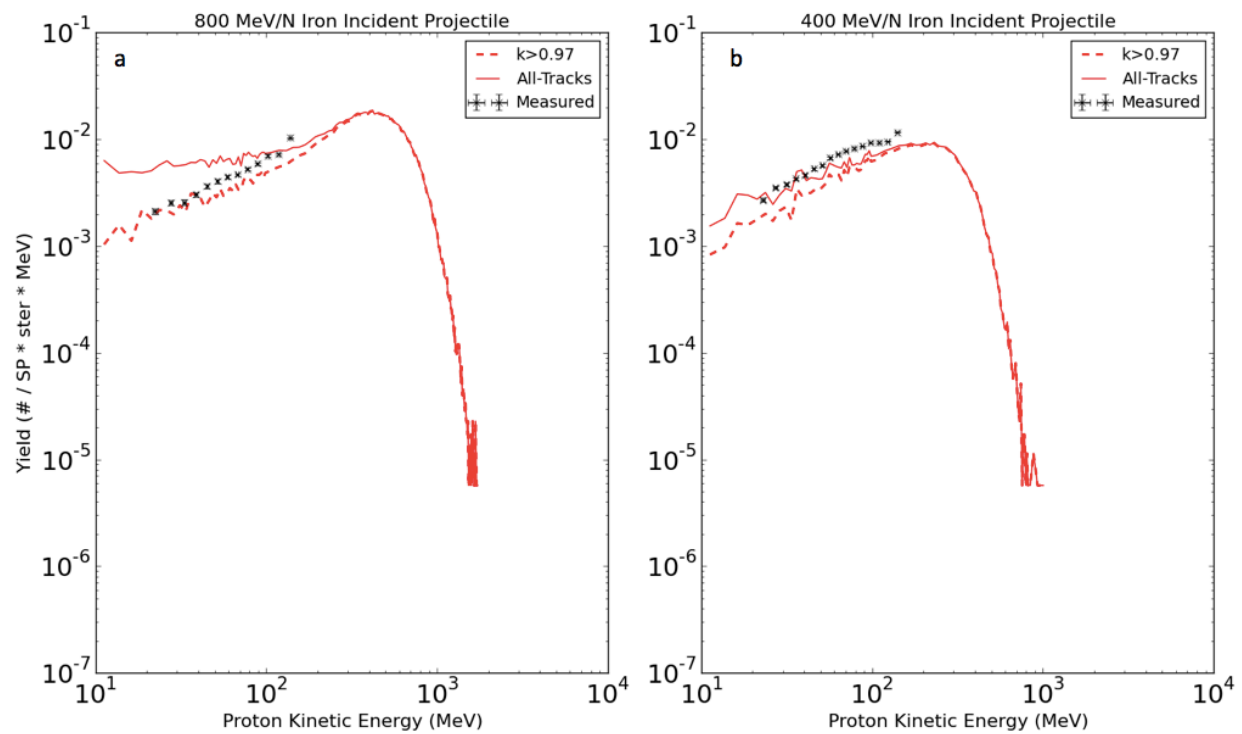


Figure 34. Experimentally-measured and MCNP-simulated DDTT protons yields for a) 800 and b) 400 MeV/N iron on 20 g/cm² Al US target at 10°; all proton tracks and directionally-restricted proton tracks.

prevalent in the TOF regions where isotope separation is achievable and the measurements are taken. However, for 400 MeV/N at 10° and 30° , this background source is pervasive in the measurements, and is best matched by the simulation that includes all particle tracks.

The success of the Monte Carlo transport codes at replicating the measured light ion yields with mass numbers greater than one is related to the mass of the projectile. For iron projectiles, the MCNP results most closely resembled the measurements in spectral shape, and in general, were closest to predicting the magnitude of the light ion yields. MCNP matched the magnitude of deuteron measurements satisfactorily, but struggled to reproduce the magnitudes of the $A \geq 3$ fragments while predominantly replicating the shape of the spectra. PHITS results underestimated the measured yields substantially for the light ions with $A \geq 3$. This is possibly due to the limitations of QMD models in producing secondary particles in the pre-equilibrium phase of the reactions at the kinetic energies encountered in this experiment [38].

For helium projectiles, PHITS is the most suitable tool for replicating the yields for all the light ions $A > 1$. The pre-equilibrium and coalescence mechanisms in LAQGSM and ISABEL are not optimized for producing light ions with high kinetic energies at forward angles [31], [43]. Special care has been taken in INCL4.6 and INCL-ELF to incorporate knockout reactions which better match the light ion yields at forward directions [29]. Likewise, INCL4.6 includes Coulomb deflection of projectiles which is important for replicating the measured yields of helium fragments.

VI. CONCLUSIONS AND FUTURE WORK

This dissertation includes a series of light ion measurements taken in March 2016 and November 2016 at the NASA Space Radiation Laboratory (NSRL). Iron, helium, and proton incident projectiles at 400 and 800 MeV/N bombarded upstream aluminum targets of 20, 40, and 60 g/cm² with an additional 60 g/cm² aluminum target set 3.5 m downstream. Double differential thick-target yields (DDTT) were calculated for protons at six positions from 10° to 135° off beam axis. Deuterons and tritons were additionally measured from 10° to 45° at minimum, while helium-3 and helium-4 ions were measured at 10° and 30°.

Proton measurements were generally well-replicated by the Monte Carlo transport codes MCNP and PHITS. The success of the transport codes in predicting the yields of mass number (A) > 1 light ions was dependent on the mass of the incident projectile. MCNP was best at modeling the yields of these light ions when handling the reactions of iron projectiles, while the results stemming from helium projectiles were best modeled by PHITS. These findings are consistent with the shortcomings of the physics models used by these transport codes to produce cross sections for interactions which have not been measured.

Future work includes the integration of a sampling ADC to the data acquisition system to digitize the pulse output from each detector on an event-by-event basis. This will allow for the collection of more information on the detection signals, such as the pulse amplitude, to allow for more advanced PSD techniques and hopefully aid in light ion discrimination for events with fast times of flight. Examples of such work has been done to identify heavy ions [44]. Additionally, the results presented in this work further suggest the importance of measuring double differential cross sections of light ion fragments $A > 1$, produced by iron and helium projectile interactions in light targets such as aluminum. Measured cross sections for these reactions do not exist [8] and once generated they will help fine tune the physics models used by radiation transport codes model these reactions of high importance in space radiation applications.

The double differential thick-target yields of light ions presented in this work are the initial contributions to a database created by the University of Tennessee, which will be used by NASA Langley Research Center to generate uncertainty quantification metrics and benchmark radiation transport codes used in spaceflight mission planning. The transport of light ions is essential for the most accurate calculations of chronic exposures to estimate the risks of long-duration missions.

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APPENDICES

APPENDIX I

Table 12. Logic units

Manufacturer	Logic Unit
Wiener	CC-USB CAMAC Controller with USB interface
CAEN	HVPS SY5527 (Geco 2020 software)
Bertan	HVPS Model 323
CAEN	16 Channel CFD Model N843
LeCroy	Multiplicity Logic Unit Model 380A
-	Majority Coincidence Model C314/NL
LeCroy	Dual Gate Generator Model 222
P/S	Quad Gate/Delay Generator Model 794
LeCroy	Logic Fan In/Fan Out Model 429
LeCroy	Octal Discriminator Model 623
LeCroy	Octal Discriminator Model 623B
Joerger	Scaler Model S12
-	Japanese Module 6 Ch. PSD
LeCroy	8 Channel TDC Model 2228A
LeCroy	12 Channel ADC Model 2249A
LeCroy	12 Channel ADC Model 2249W
BNL	Splitters
BNL	Delays

Table 13. Centroid and FWHM of prompt gamma peaks for all projectiles on 20 g/cm² Al US target.

Detector	Centroid (channel)					
	FWHM (ns)					
	400 MeV/N Fe	800 MeV/N Fe	400 MeV/N He	800 MeV/N He	400 MeV H	800 MeV H
10°	773	775	787	668	775	778
	0.95	1.19	0.94	1.16	1.41	1.37
30°	765	768	779	659	767	770
	0.95	0.95	0.94	0.93	0.94	0.92
45°	766	769	781	660	768	771
	0.95	0.95	0.94	1.39	1.18	0.92
60°	794	796	808	688	795	798
	1.19	1.19	1.18	1.16	1.18	1.15
80°	790	793	804	682	791	794
	1.19	1.19	1.18	1.39	1.18	1.37
135°	806	808	820	696	806	809
	1.19	1.19	1.18	1.16	1.18	1.15

Table 14. Centroid and FWHM of prompt gamma peaks for all projectiles on 40 g/cm² Al US target.

Detector	Centroid (channel)					
	FWHM (ns)					
	400 MeV/N Fe	800 MeV/N Fe	400 MeV/N He	800 MeV/N He	400 MeV H	800 MeV H
10°	772	775	787	668	775	778
	0.95	1.19	0.94	1.16	1.65	1.37
30°	765	768	779	659	767	770
	0.95	0.95	0.94	0.93	0.94	0.92
45°	766	769	780	660	768	771
	0.95	1.19	0.94	1.39	1.18	0.92
60°	793	796	808	688	795	798
	1.19	1.19	1.18	1.16	1.18	1.15
80°	789	793	804	681	790	794
	1.19	1.42	1.18	1.39	1.18	1.60
135°	806	808	820	696	807	810
	1.43	1.42	1.41	1.39	1.41	1.37

Table 15. Centroid and FWHM of prompt gamma peaks for all projectiles on 60 g/cm² Al US target.

Detector	Centroid (channel)					
	FWHM (ns)					
	400 MeV/N Fe	800 MeV/N Fe	400 MeV/N He	800 MeV/N He	400 MeV H	800 MeV H
10°	772	775	787	668	774	778
	0.95	1.19	0.94	1.16	1.18	1.37
30°	764	768	779	660	767	769
	1.19	1.19	0.94	0.93	1.18	0.92
45°	765	769	780	660	768	771
	1.19	1.19	1.18	1.39	0.94	1.15
60°	793	796	807	688	794	798
	1.43	1.42	1.18	1.16	1.18	1.37
80°	788	792	803	682	790	794
	1.43	1.42	1.41	1.39	1.65	1.60
135°	807	809	820	696	808	810
	1.43	1.90	1.65	1.39	1.65	1.60

Table 16. Maximum measured kinetic energy per nucleon, averaged over US target thickness

	Measured Kinetic Energy per Nucleon (MeV/N)											
Projectile, Kinetic Energy	Fe 400 MeV/N						Fe 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	142.2	136.6	143.5	105.0	100.7	83.4	136.9	137.9	141.2	99.3	694.1	150.0
Deuteron	88.4	94.3	91.1	83.3	73.7		85.4	91.0	82.1	75.9	55.1	
Triton	87.8	101.3	97.2				101.4	100.5	96.0	58.4		
Helium-3	144.3	125.3					134.2	140.3				
Helium-4	136.7						149.9	142.4				
Projectile, Kinetic Energy	He 400 MeV/N						He 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	139.1	127.4	134.6	117.4	213.6	151.0	136.1	131.7	141.2	132.2	401.2	192.1
Deuteron	90.7	82.7	89.5	78.3			99.3	97.5	115.2	104.2		
Triton	93.7	84.1	93.4				98.6	67.6				
Helium-3	141.1	124.6					147.3	123.3				
Helium-4	142.7	97.7										
Projectile, Kinetic Energy	H 400 MeV						H 800 MeV					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	128.1	281.8	364.8	285.1	86.9	114.7	130.5	124.8	125.1	725.3	614.3	185.1
Deuteron	130.6	72.1	67.7				151.9	121.5	128.0	82.5		
Triton												
Helium-3												
Helium-4												

Table 17. Total median graphical cut uncertainties, fractional values.

Projectile, Kinetic Energy	Fe 400 MeV/N						Fe 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.01	0.01	0.02	0.03	0.01	0.02	0.13	0.15	0.15	0.11	0.15	0.14
Deuteron	0.01	0.01	0.02	0.15	0.01		0.13	0.15	0.16	0.14	0.15	
Triton	0.01	0.01	0.02				0.14	0.15	0.16	0.14		
Helium-3	0.01	0.01					0.13	0.15				
Helium-4	0.01	0.01					0.13	0.15				
Projectile, Kinetic Energy	He 400 MeV/N						He 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.01	0.01	0.01	0.02	0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Deuteron	0.03	0.01	0.01	0.01			<0.01	<0.01	<0.01	<0.01		
Triton	0.01	0.01	0.01				<0.01	<0.01	<1%			
Helium-3	0.01	0.01					<0.01	<0.01				
Helium-4	0.01	0.01					<1%	<1%				
Projectile, Kinetic Energy	H 400 MeV						H 800 MeV					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.03	0.02	0.03	0.03	0.12	0.06	0.02	0.02	0.02	0.02	0.03	0.03
Deuteron	0.04	0.05	0.09				0.02	0.03	0.04	0.04		
Triton												
Helium-3												
Helium-4												

Table 18. Total median systematic uncertainties, fractional values.

Projectile, Kinetic Energy	Fe 400 MeV/N						Fe 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.06	0.06	0.05	0.06	0.02	0.07	0.18	0.19	0.18	0.13	0.16	0.21
Deuteron	0.06	0.06	0.05	0.17	0.02		0.18	0.19	0.18	0.16	0.16	
Triton	0.06	0.06	0.05				0.19	0.19	0.18	0.16		
Helium-3	0.06	0.06					0.18	0.19				
Helium-4	0.06						0.18	0.19				
Projectile, Kinetic Energy	He 400 MeV/N						He 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.06	0.05	0.05	0.05	0.02	0.07	0.05	0.05	0.04	0.03	0.02	0.06
Deuteron	0.08	0.06	0.05	0.05			0.05	0.05	0.04	0.03		
Triton	0.06	0.06	0.05				0.05	0.05				
Helium-3	0.06	0.06					0.05	0.05				
Helium-4	0.06	0.06										
Projectile, Kinetic Energy	H 400 MeV						H 800 MeV					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.06	0.07	0.07	0.06	0.13	0.11	0.07	0.06	0.05	0.05	0.05	0.08
Deuteron	0.09	0.10	0.13				0.09	0.07	0.08	0.07		
Triton												
Helium-3												
Helium-4												

Table 19. Median statistical uncertainties for experimental measurements, fractional values.

Projectile, Kinetic Energy	Fe 400 MeV/N						Fe 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.02	0.05	0.07	0.09	0.30	0.18	0.03	0.05	0.06	0.07	0.22	0.17
Deuteron	0.06	0.13	0.29	0.33	0.46		0.08	0.13	0.20	0.25	0.46	
Triton	0.10	0.34	0.51				0.15	0.33	0.50	0.54		
Helium-3	0.06	0.53					0.08	0.38				
Helium-4	0.04	0.40					0.06	0.56				
Projectile, Kinetic Energy	He 400 MeV/N						He 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.05	0.06	0.08	0.09	0.34	0.29	0.06	0.10	0.09	0.10	0.21	0.27
Deuteron	0.11	0.17	0.26	0.33			0.16	0.24	0.27	0.36		
Triton	0.34	0.50	0.58				0.44	0.58	0.49			
Helium-3	0.18	0.54					0.41	0.58				
Helium-4	0.41	0.71					0.63	0.63				
Projectile, Kinetic Energy	H 400 MeV						H 800 MeV					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.05	0.06	0.07	0.10	0.41	0.26	0.04	0.07	0.08	0.06	0.17	0.15
Deuteron	0.12	0.27	0.35				0.11	0.22	0.26	0.30		
Triton												
Helium-3												
Helium-4												

Table 20. Median statistical uncertainties for MCNP-LAQGSM simulations, fractional values.

Projectile, Kinetic Energy	Fe 400 MeV/N						Fe 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.09	0.20	0.32	0.50	1.00	0.99	0.06	0.11	0.14	0.19	0.70	0.58
Deuteron	0.16	0.50	0.71	1.00	1.00		0.08	0.28	0.45	0.71	1.00	
Triton	0.21	0.85	1.00				0.19	0.71	1.00	1.00		
Helium-3	0.29	1.00					0.19	1.00				
Helium-4	0.29	1.00					0.23	1.00				
Projectile, Kinetic Energy	He 400 MeV/N						He 800 MeV/N					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.07	0.09	0.12	0.16	0.50	1.00	0.07	0.09	0.11	0.13	0.38	0.58
Deuteron	0.22	0.38	0.50	0.71			0.20	0.33	0.43	0.50		
Triton	0.71	1.00	1.00				0.71	1.00	1.00			
Helium-3	0.71	1.00					1.00	1.00				
Helium-4	1.00	N/A					1.00	N/A				
Projectile, Kinetic Energy	H 400 MeV						H 800 MeV					
Angle (degrees)	10	30	45	60	80	135	10	30	45	60	80	135
Proton	0.17	0.13	0.18	0.27	1.00	1.00	0.09	0.13	0.19	0.24	0.71	0.58
Deuteron	0.70	0.85	1.00				0.30	0.45	0.58	1.00		
Triton												
Helium-3												
Helium-4												

APPENDIX II

**Comparisons of experimental double differential thick-target hydrogen
isotope yield data with MCNP simulations**

400 and 800 MeV/N iron projectiles

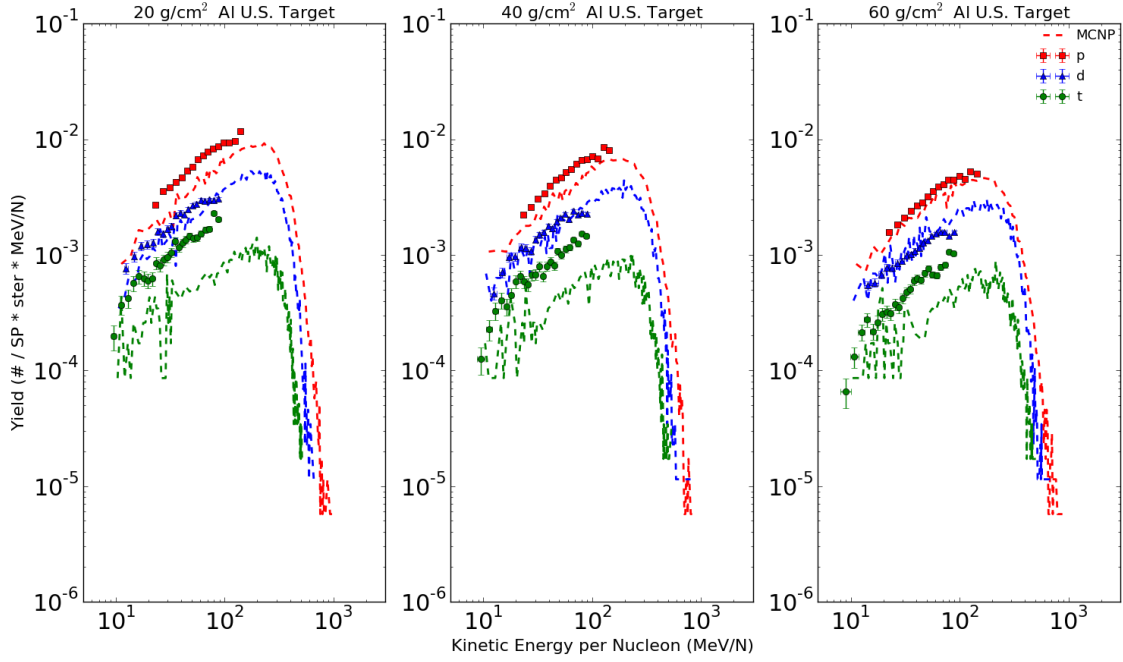


Figure 35. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 400 MeV/N iron projectiles on aluminum at 10° .

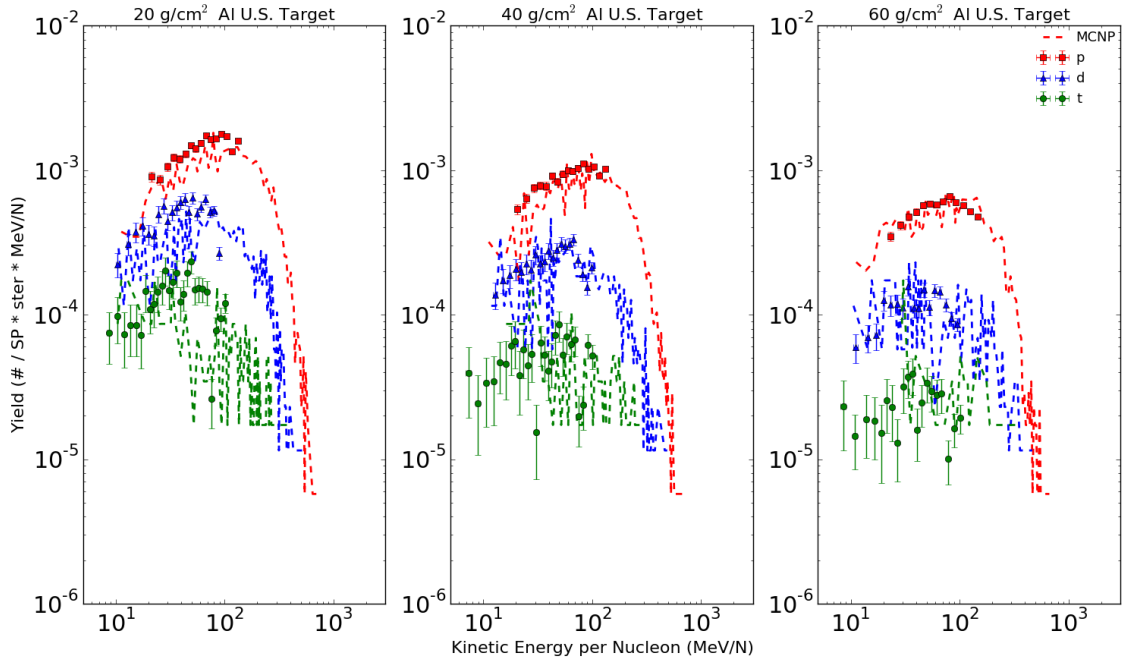


Figure 36. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 400 MeV/N iron projectiles on aluminum at 30° .

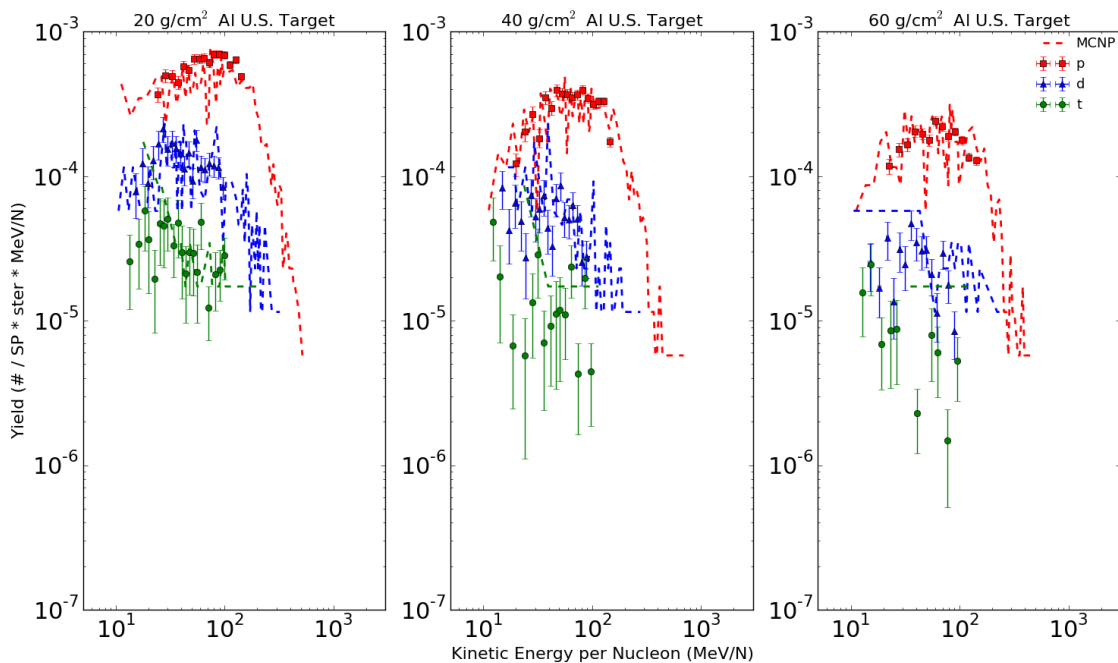


Figure 37. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 400 MeV/N iron projectiles on aluminum at 45°.

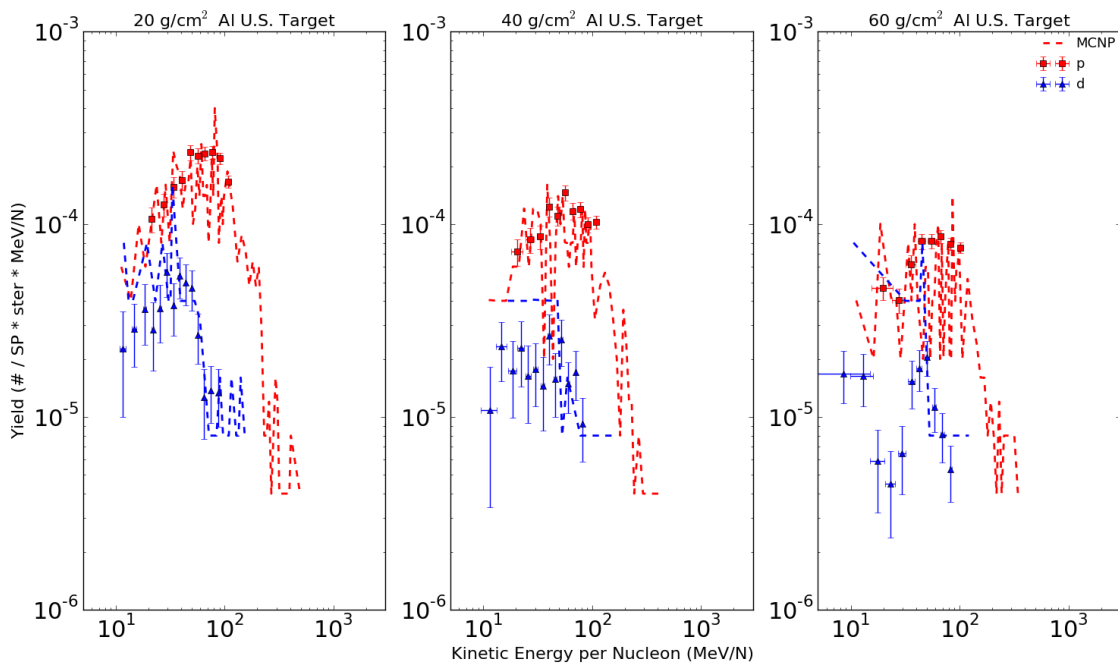


Figure 38. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 400 MeV/N iron projectiles on aluminum at 60°.

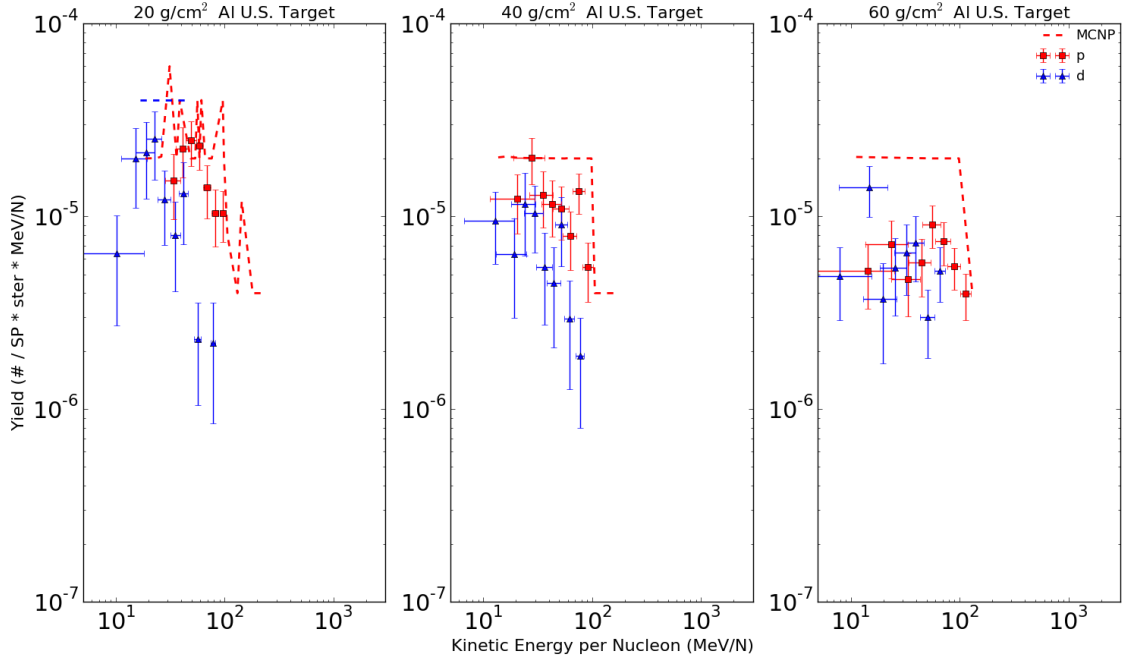


Figure 39. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 400 MeV/N iron projectiles on aluminum at 80°.

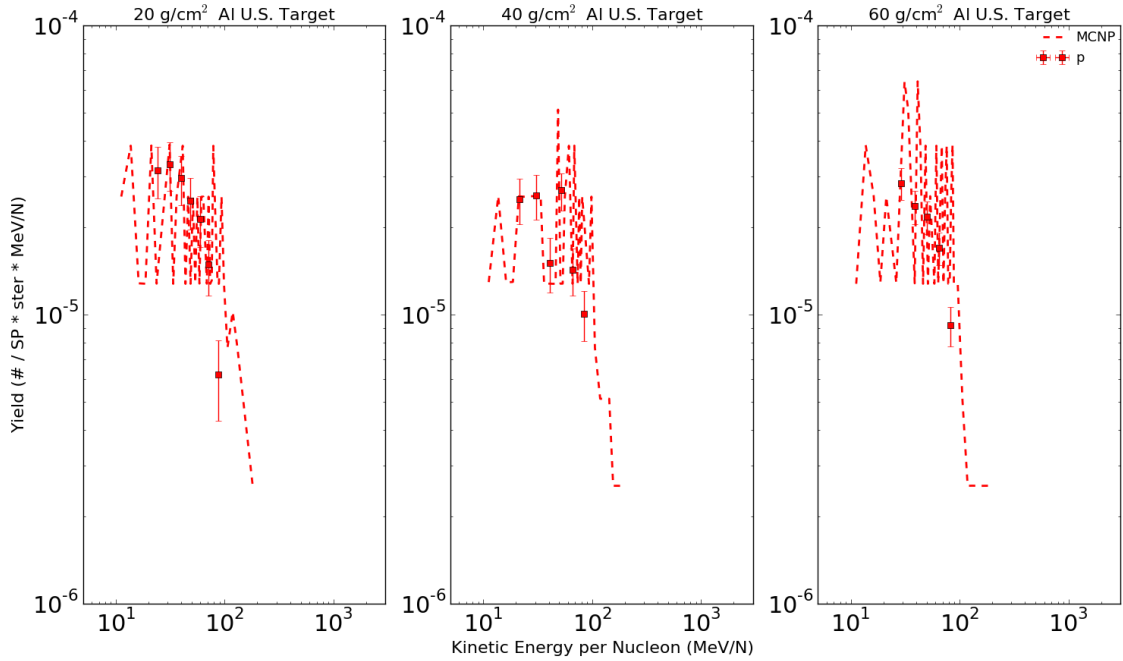


Figure 40. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 400 MeV/N iron projectiles on aluminum at 135°.

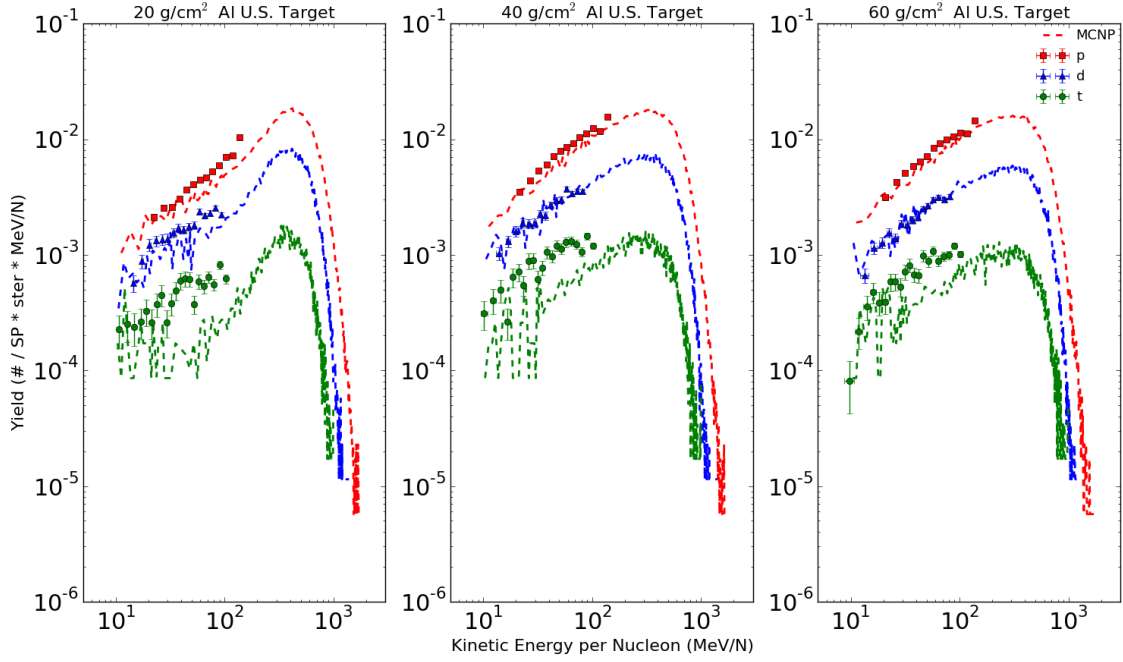


Figure 41. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 800 MeV/N iron projectiles on aluminum at 10°.

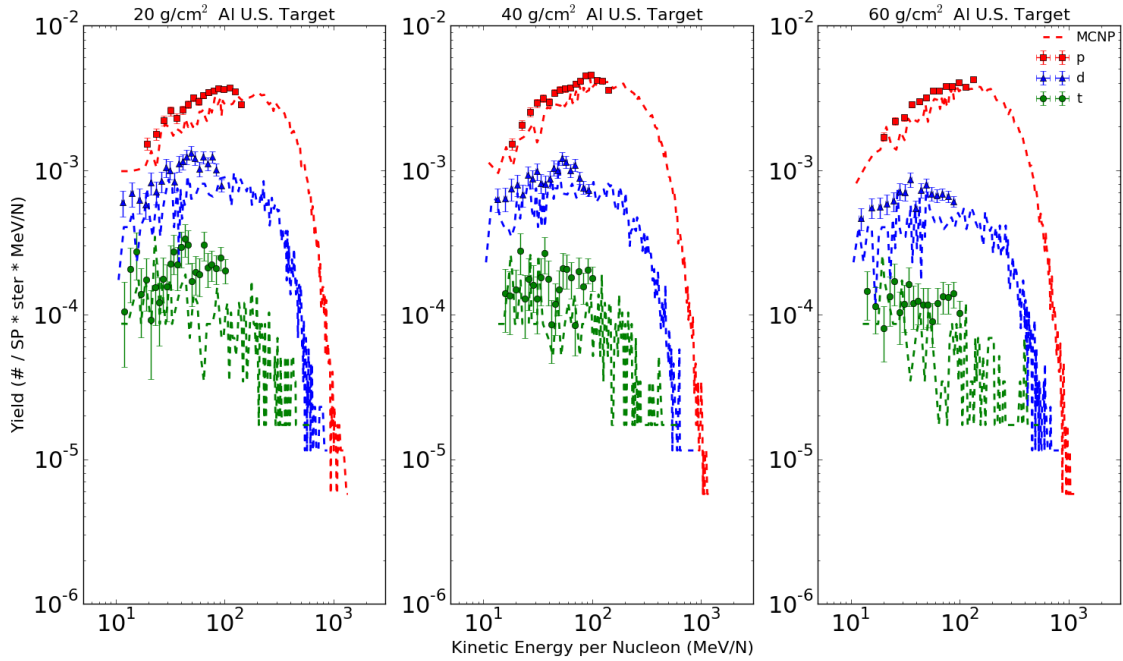


Figure 42. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 800 MeV/N iron projectiles on aluminum at 30°.

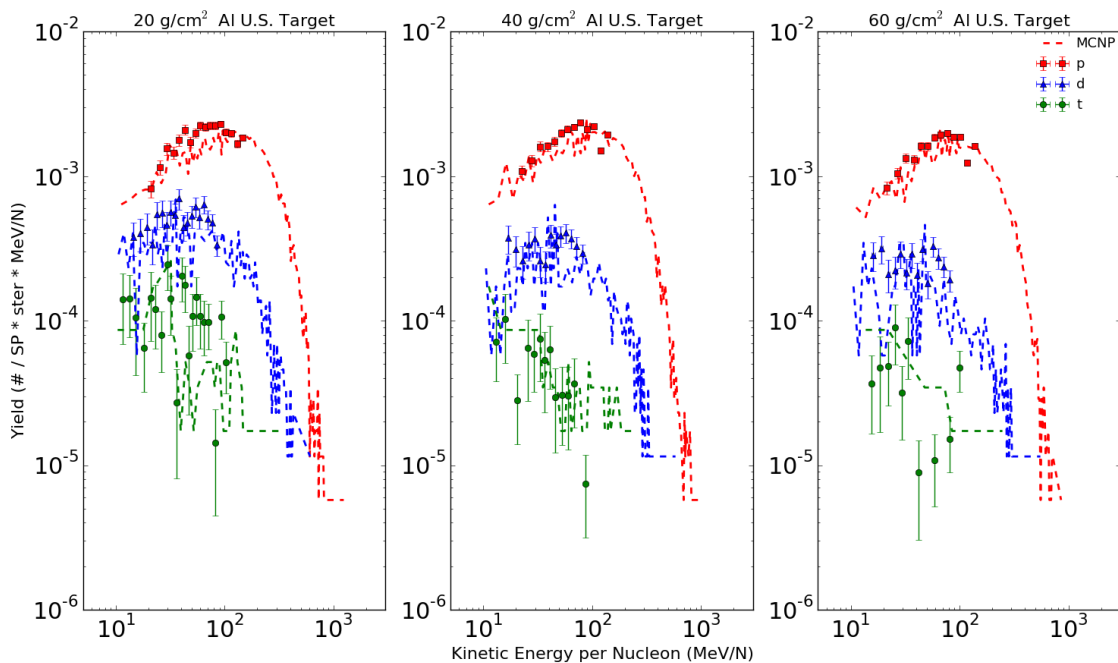


Figure 43. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 800 MeV/N iron projectiles on aluminum at 45°.

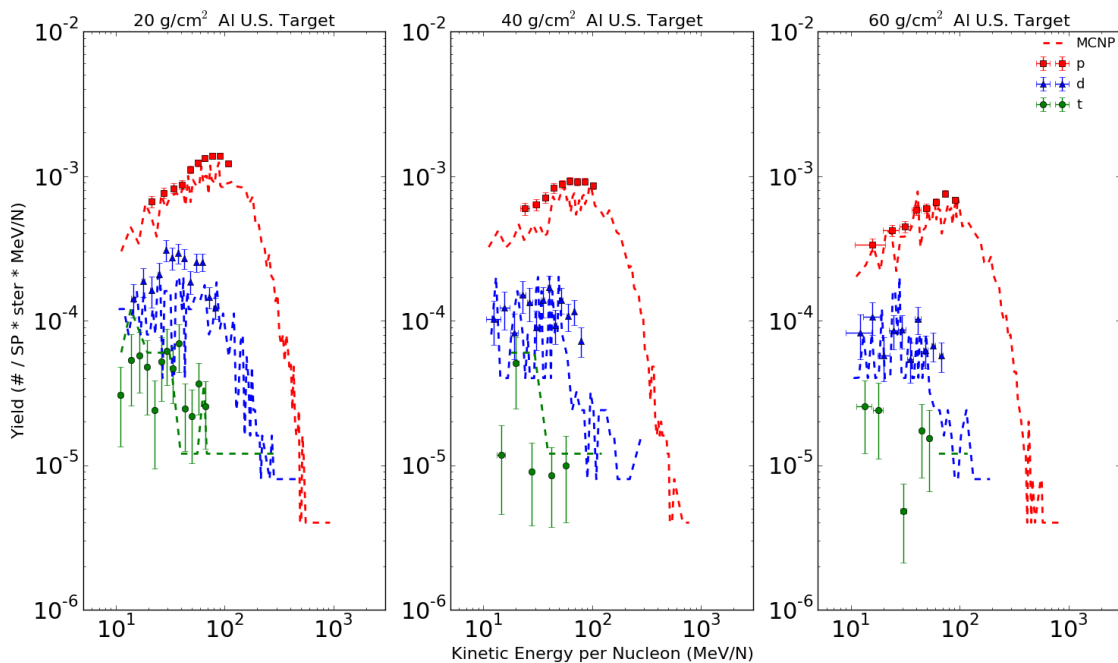


Figure 44. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 800 MeV/N iron projectiles on aluminum at 60°.

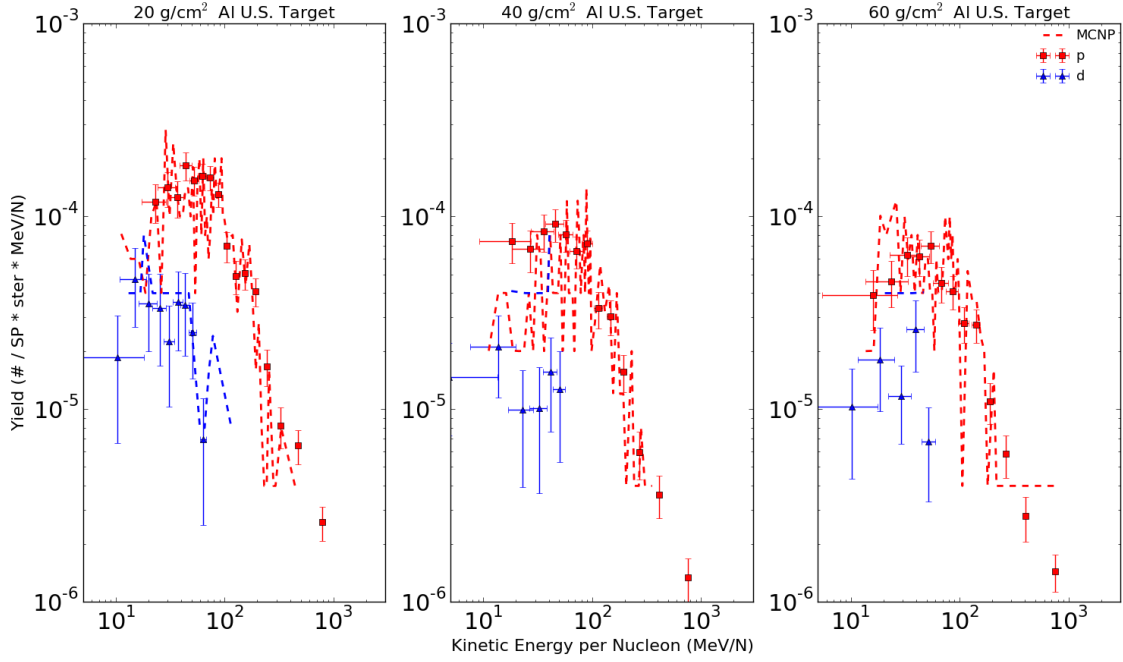


Figure 45. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 800 MeV/N iron projectiles on aluminum at 80°.

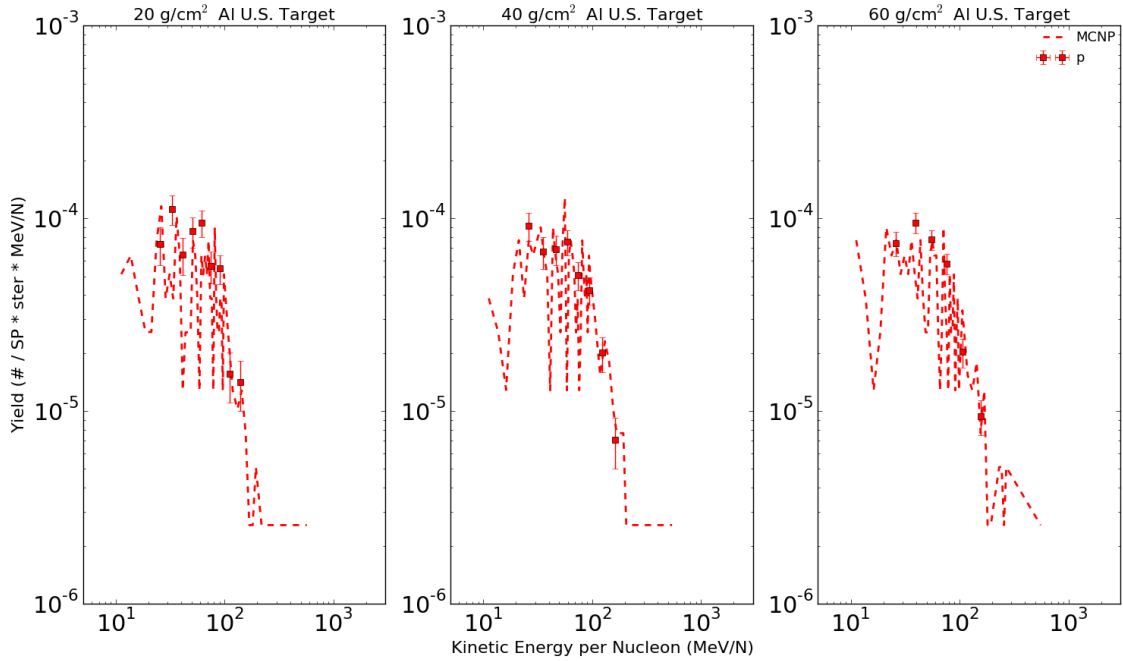


Figure 46. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 800 MeV/N iron projectiles on aluminum at 135°.

400 and 800 MeV/N helium projectiles

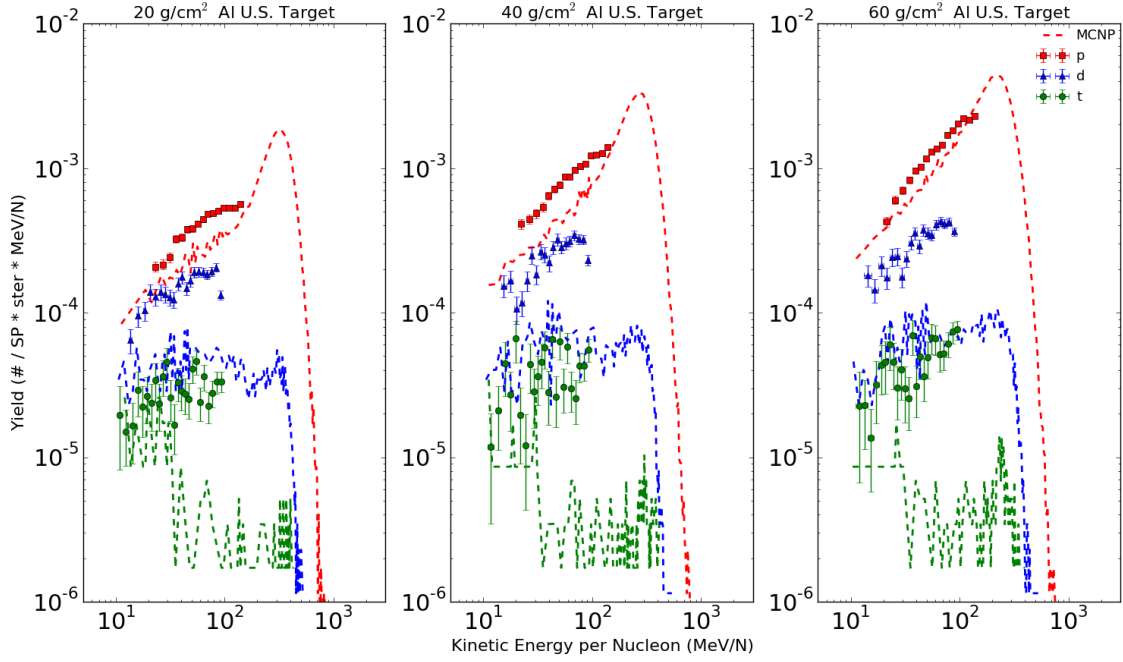


Figure 47. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 400 MeV/N helium projectiles on aluminum at 10°.

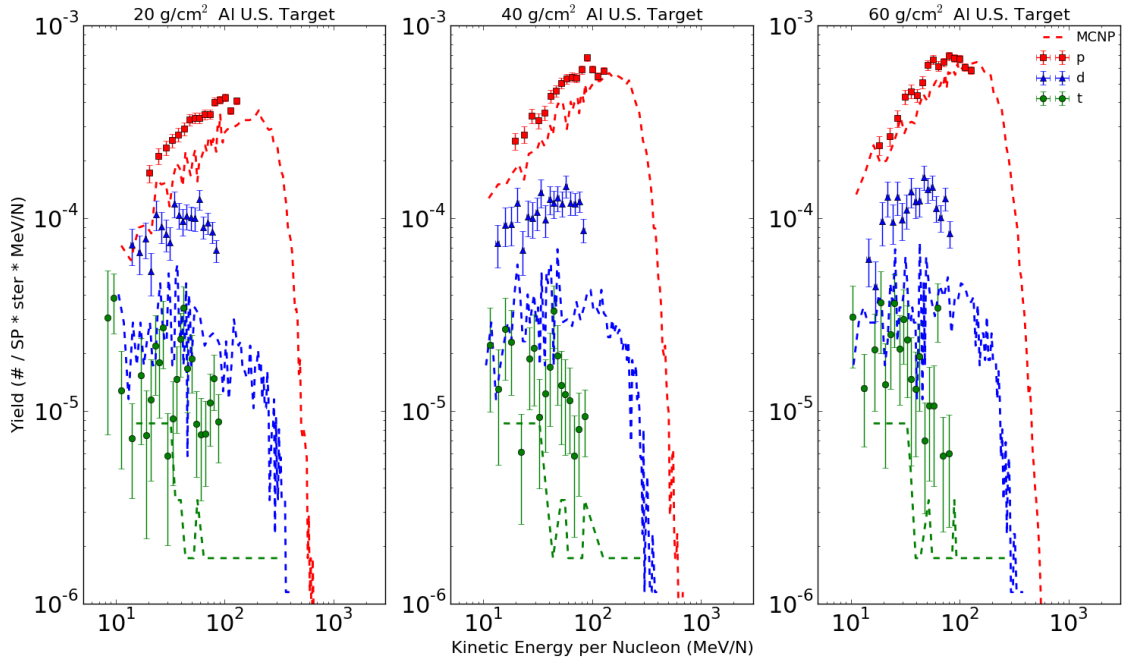


Figure 48. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 400 MeV/N helium projectiles on aluminum at 30°.

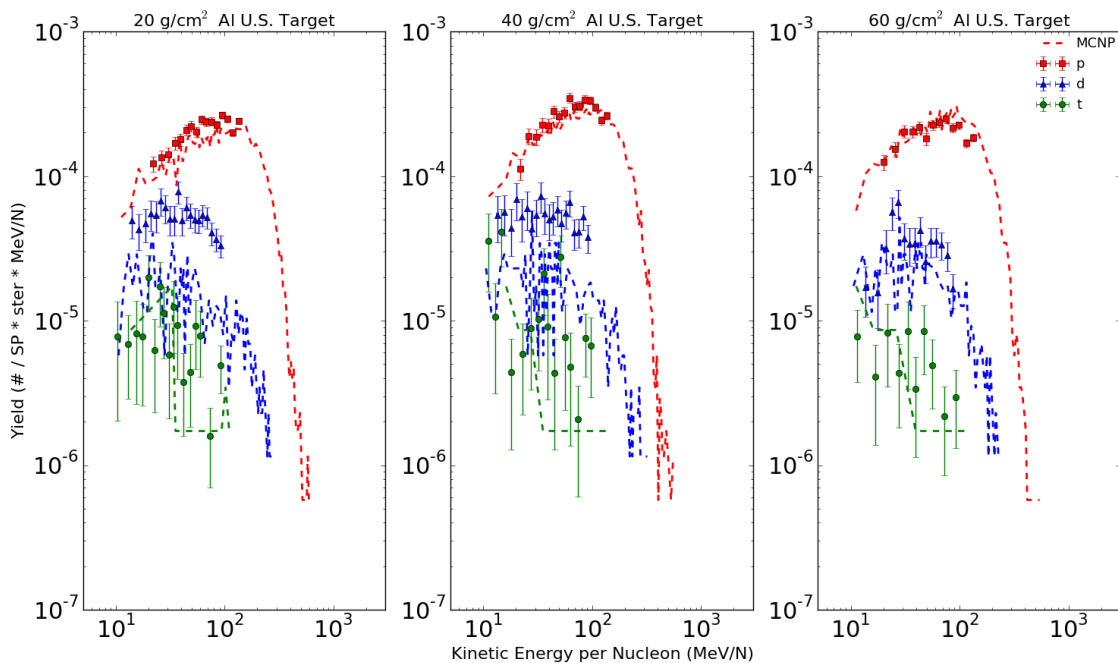


Figure 49. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 400 MeV/N helium projectiles on aluminum at 45°.

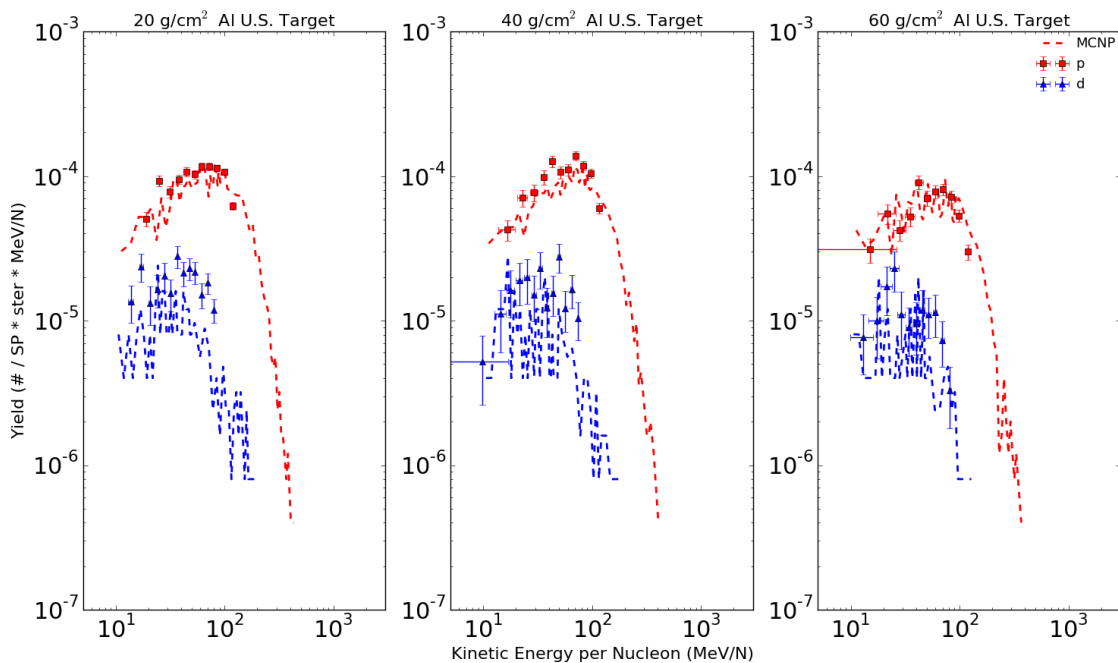


Figure 50. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 400 MeV/N helium projectiles on aluminum at 60°.

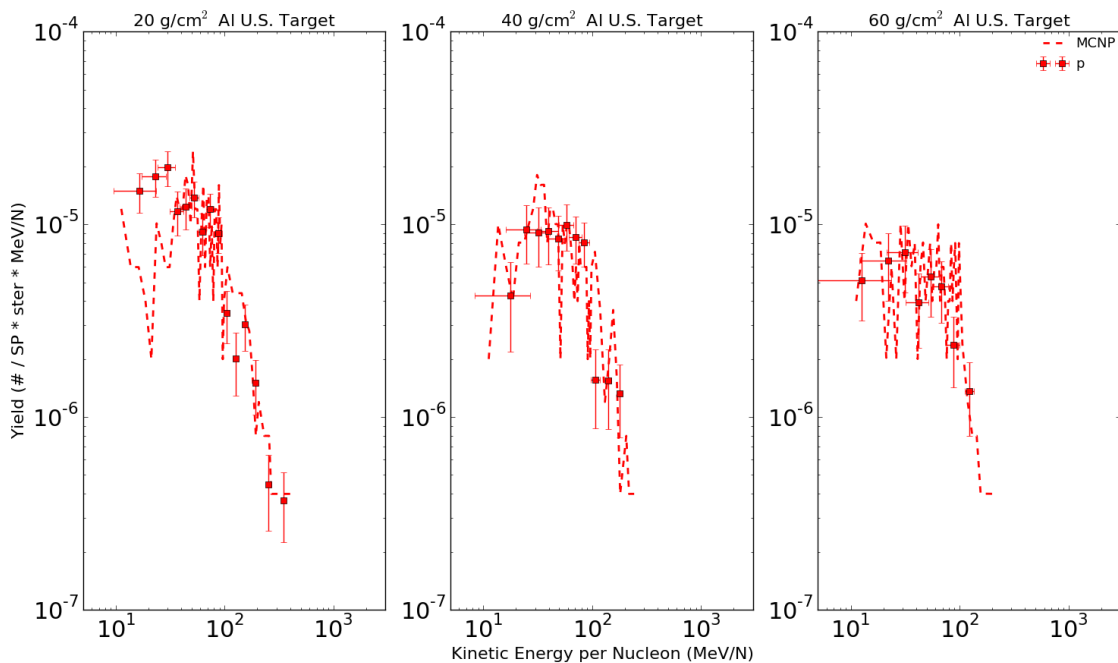


Figure 51. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 400 MeV/N helium projectiles on aluminum at 80°.

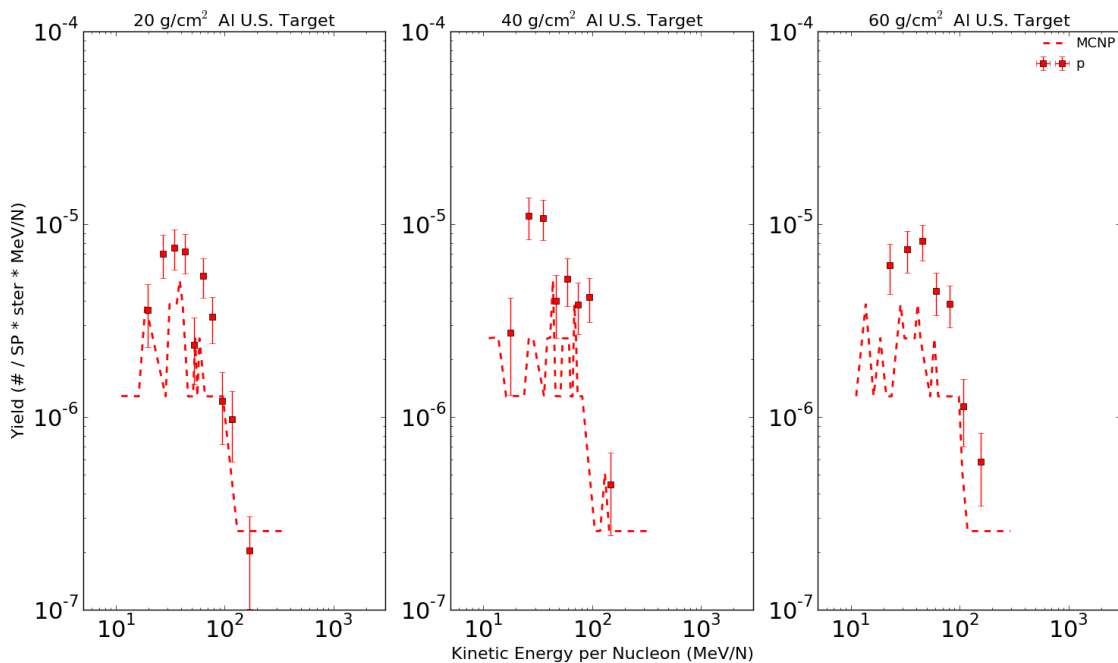


Figure 52. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 400 MeV/N helium projectiles on aluminum at 135°.

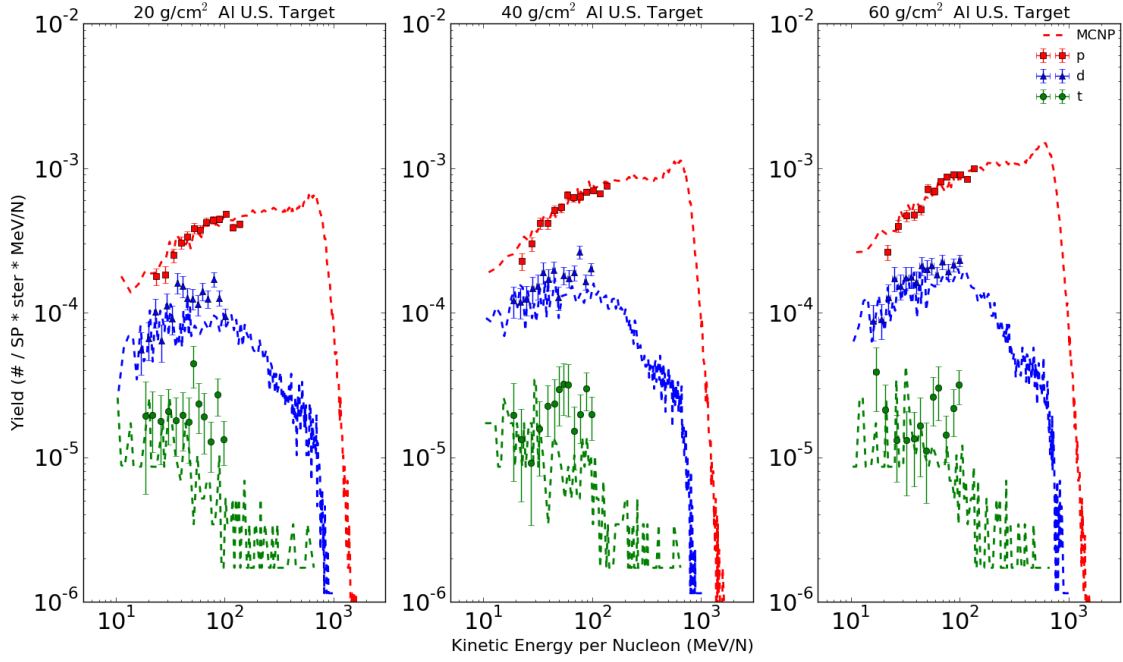


Figure 53. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 800 MeV/N helium projectiles on aluminum at 10°.

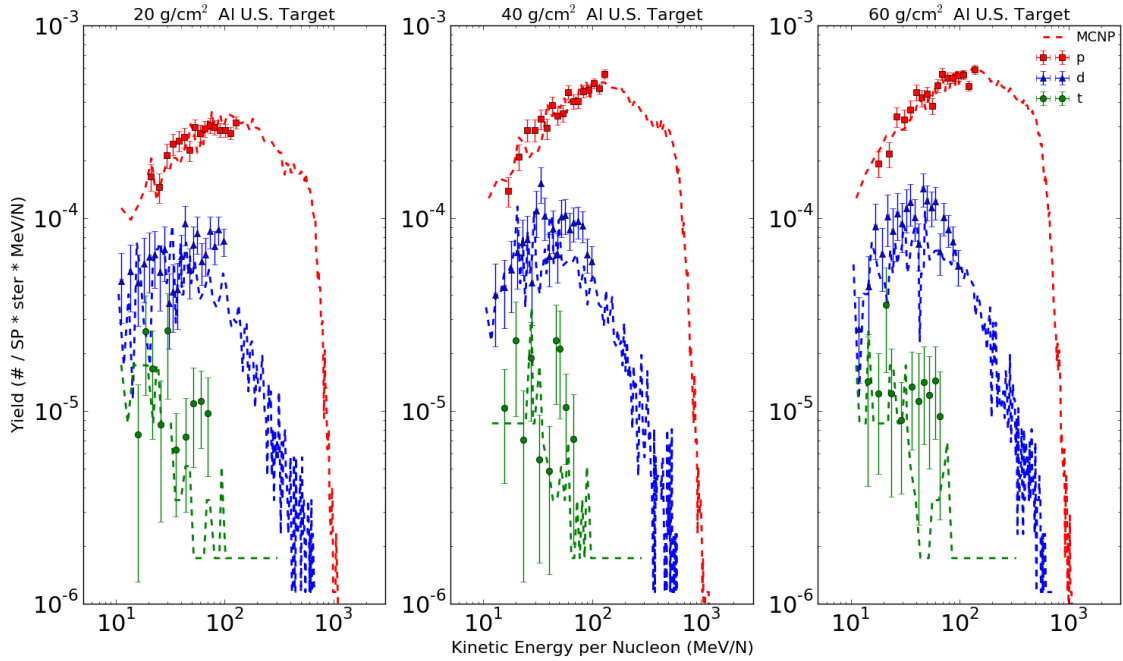


Figure 54. Comparison of MCNP-calculated and experimentally measured DDTT proton, deuteron, and triton yields for 800 MeV/N helium projectiles on aluminum at 30°.

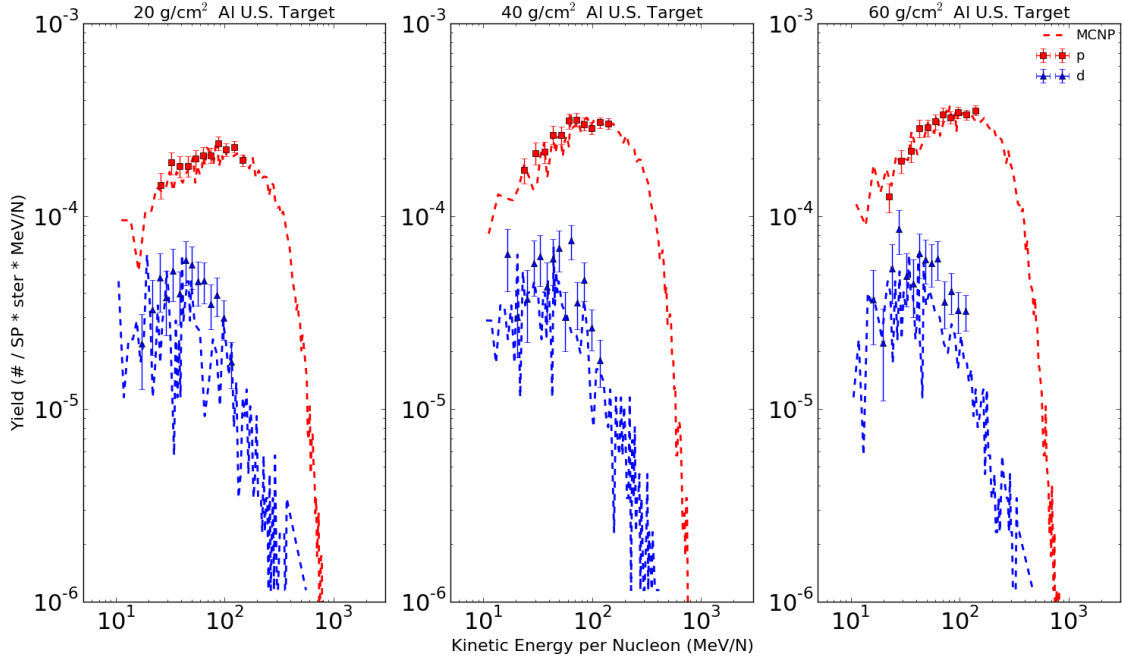


Figure 55. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 800 MeV/N helium projectiles on aluminum at 45°.

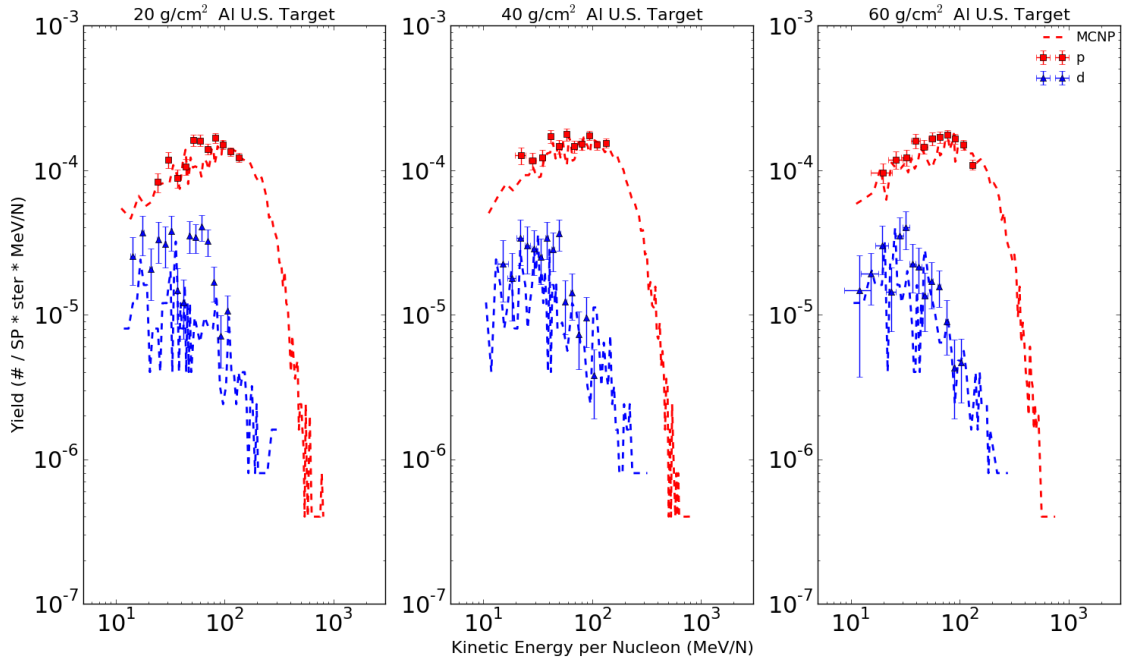


Figure 56. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 800 MeV/N helium projectiles on aluminum at 60°.

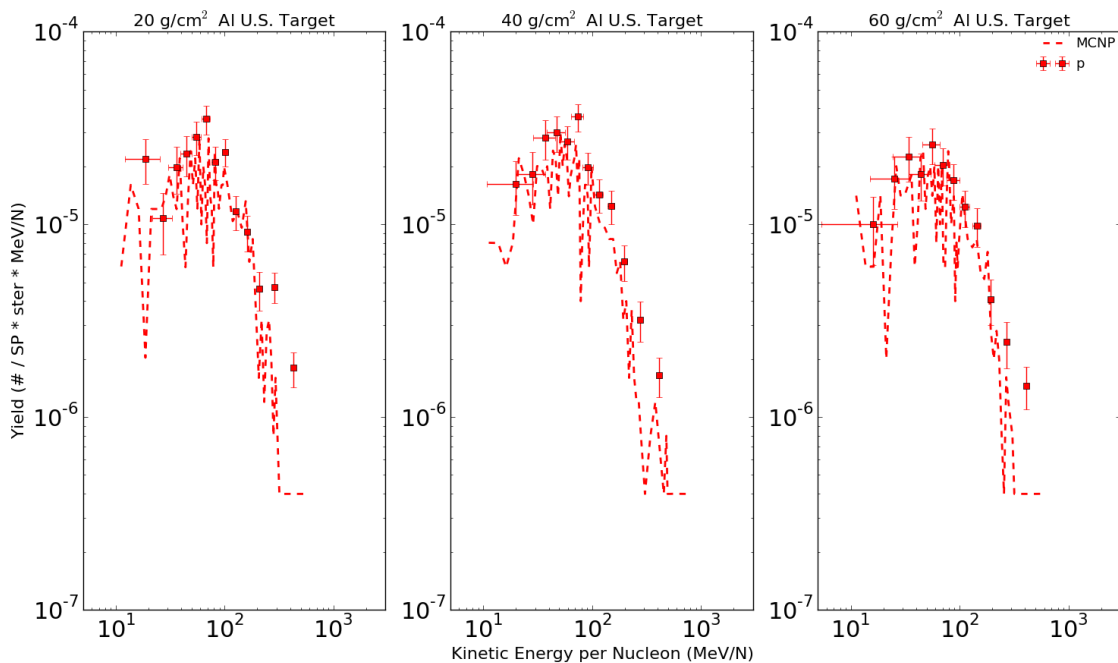


Figure 57. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 800 MeV/N helium projectiles on aluminum at 80°.

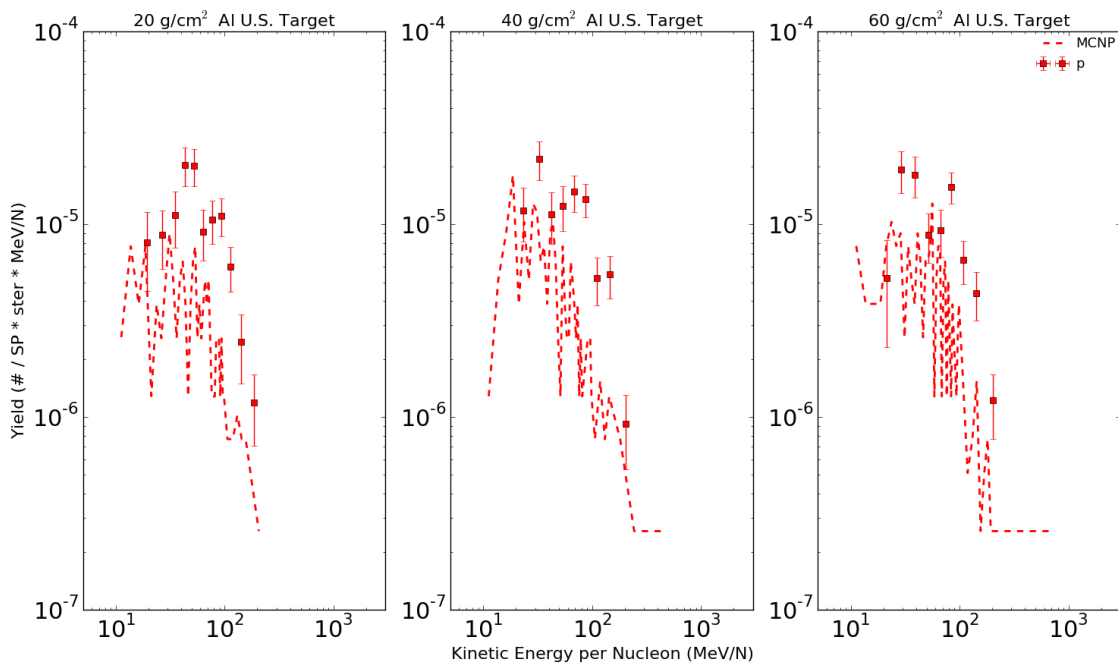


Figure 58. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 800 MeV/N helium projectiles on aluminum at 135°.

400 and 800 MeV proton projectiles

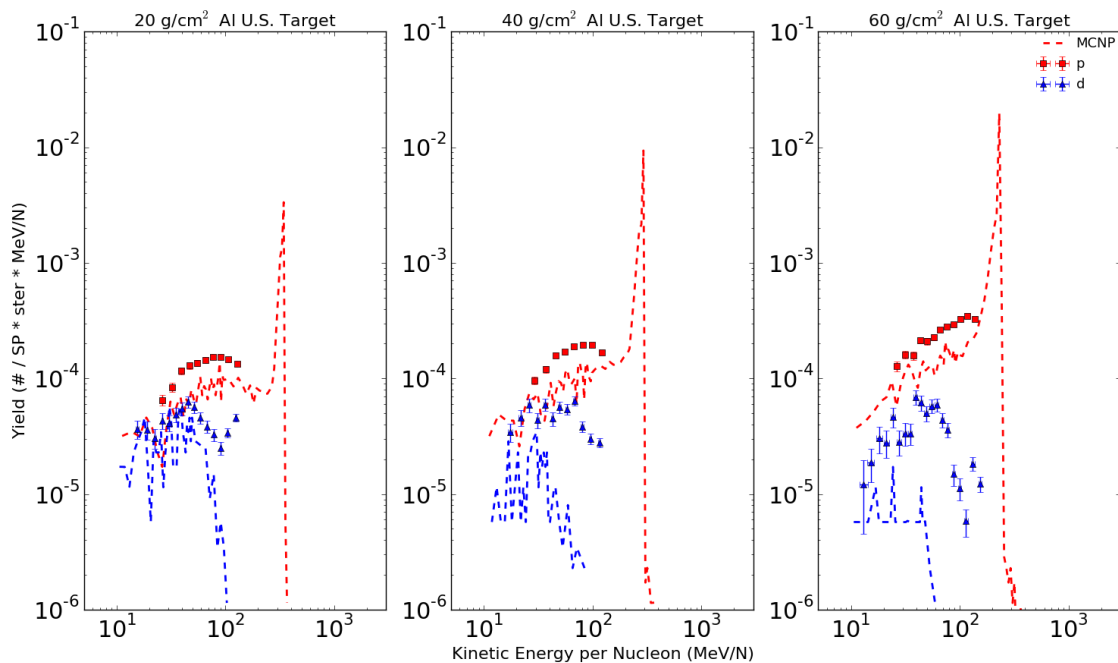


Figure 59. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 400 MeV proton projectiles on aluminum at 10° .

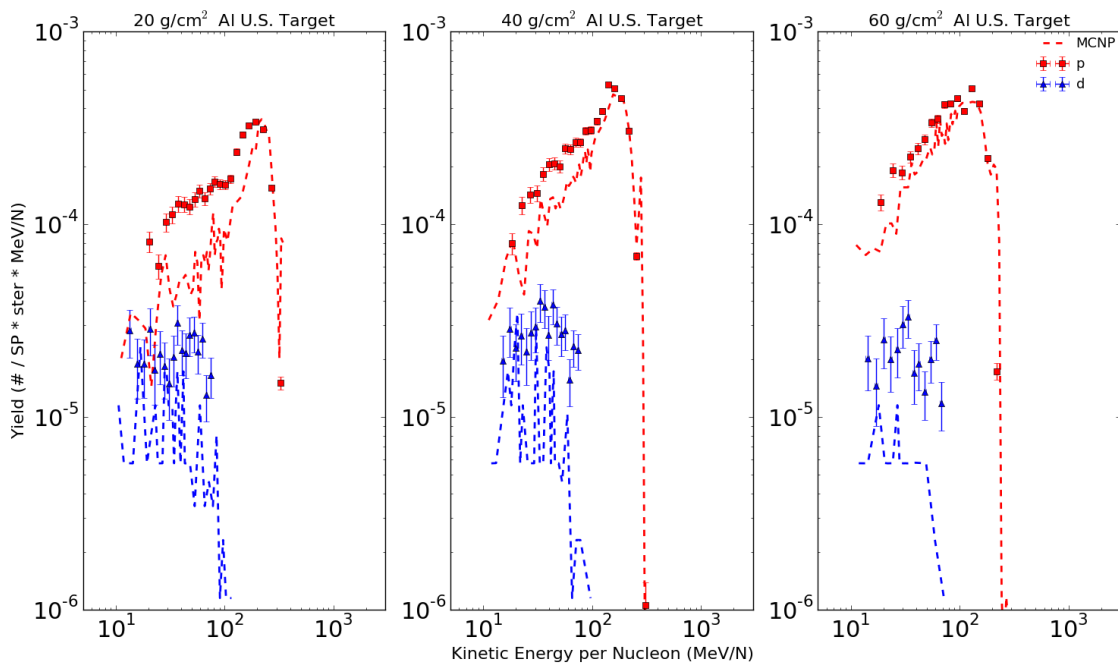


Figure 60. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 400 MeV proton projectiles on aluminum at 30° .

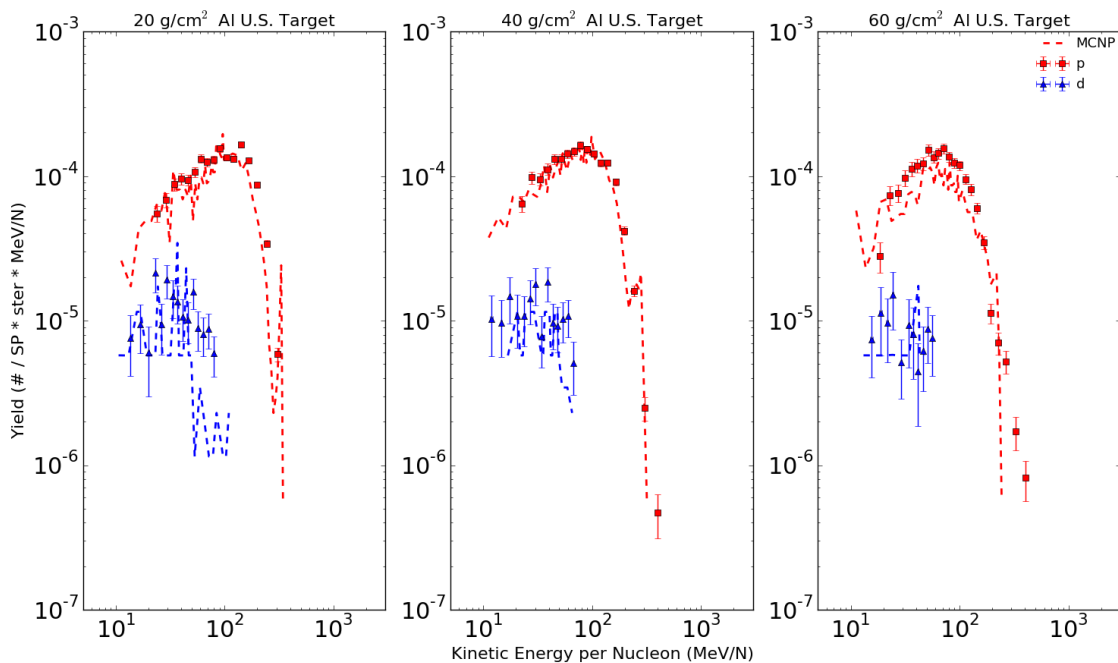


Figure 61. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 400 MeV proton projectiles on aluminum at 45°.

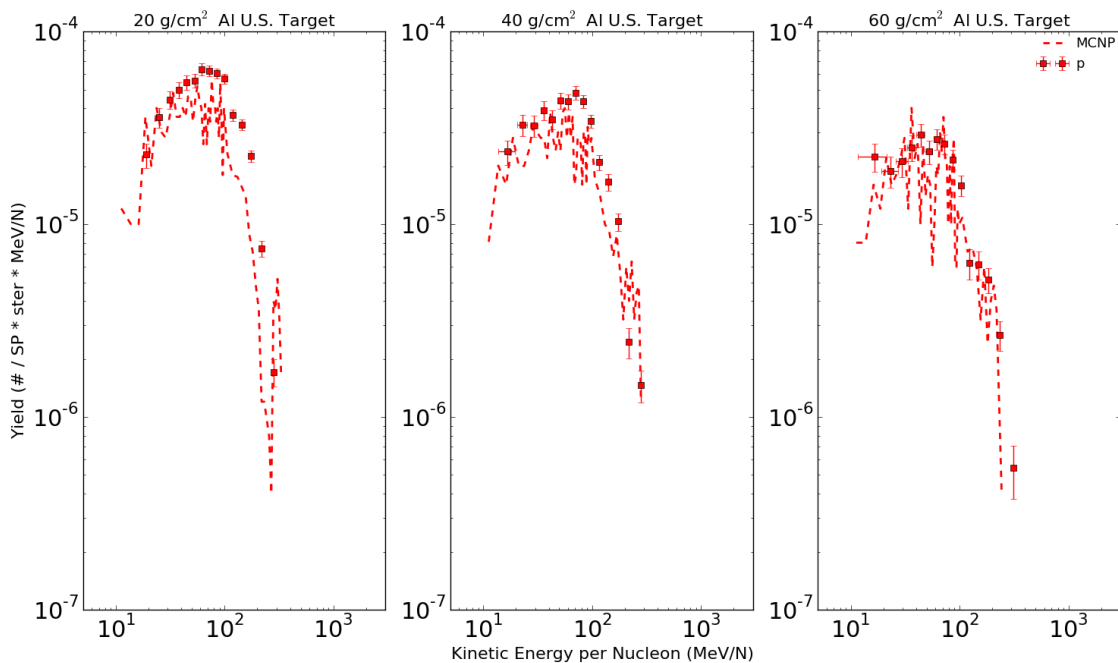


Figure 62. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 400 MeV proton projectiles on aluminum at 60°.

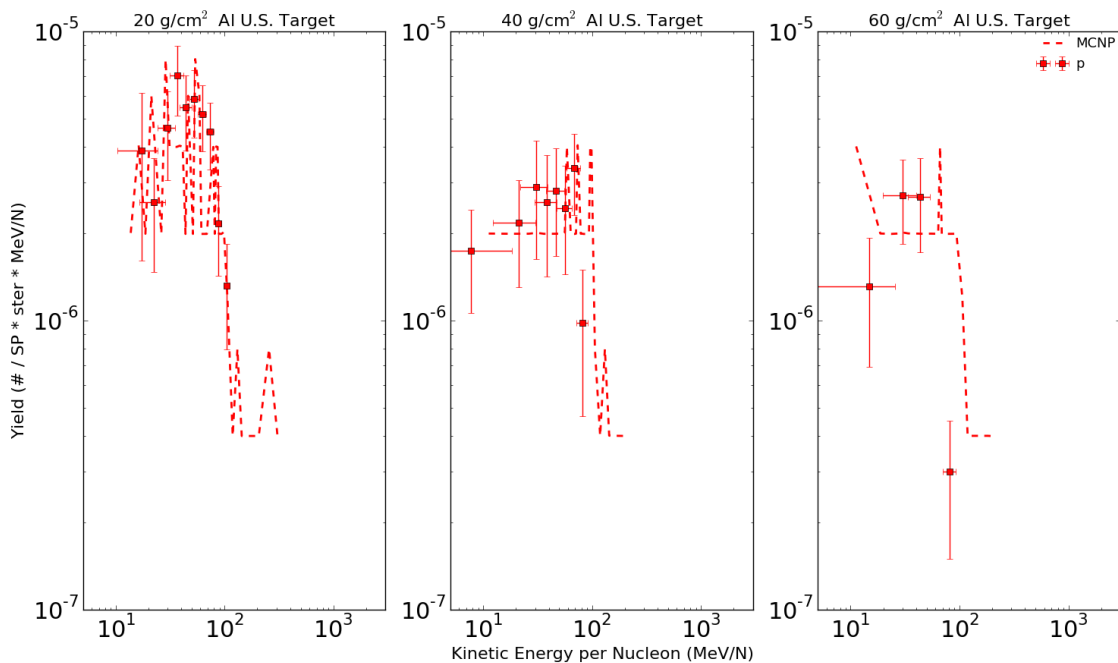


Figure 63. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 400 MeV proton projectiles on aluminum at 80°.

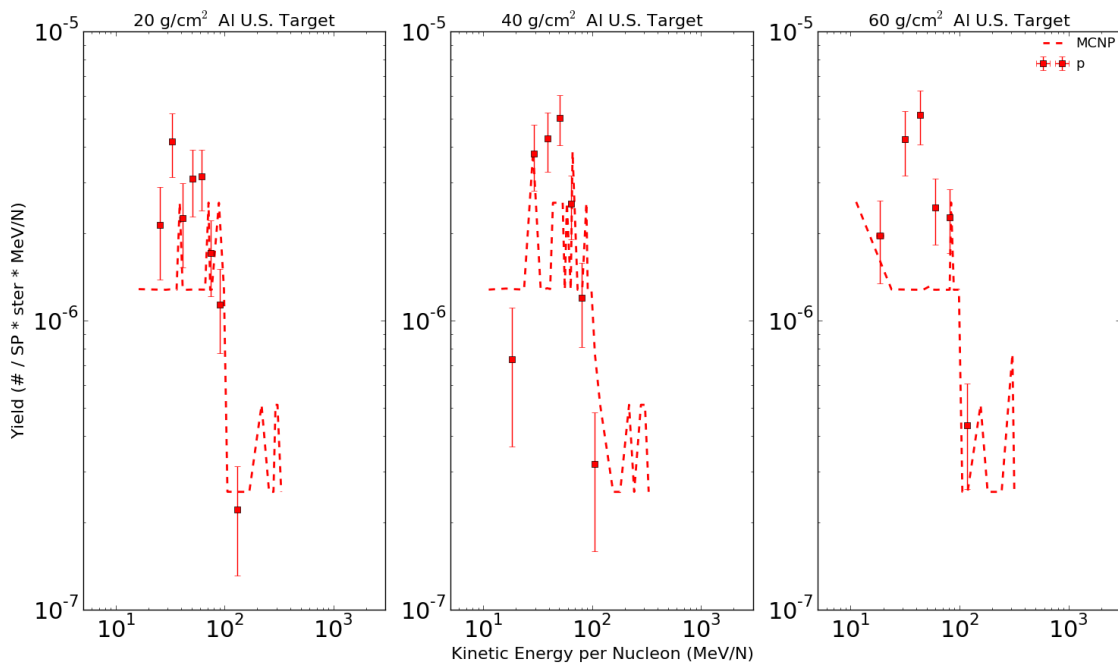


Figure 64. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 400 MeV proton projectiles on aluminum at 135°.

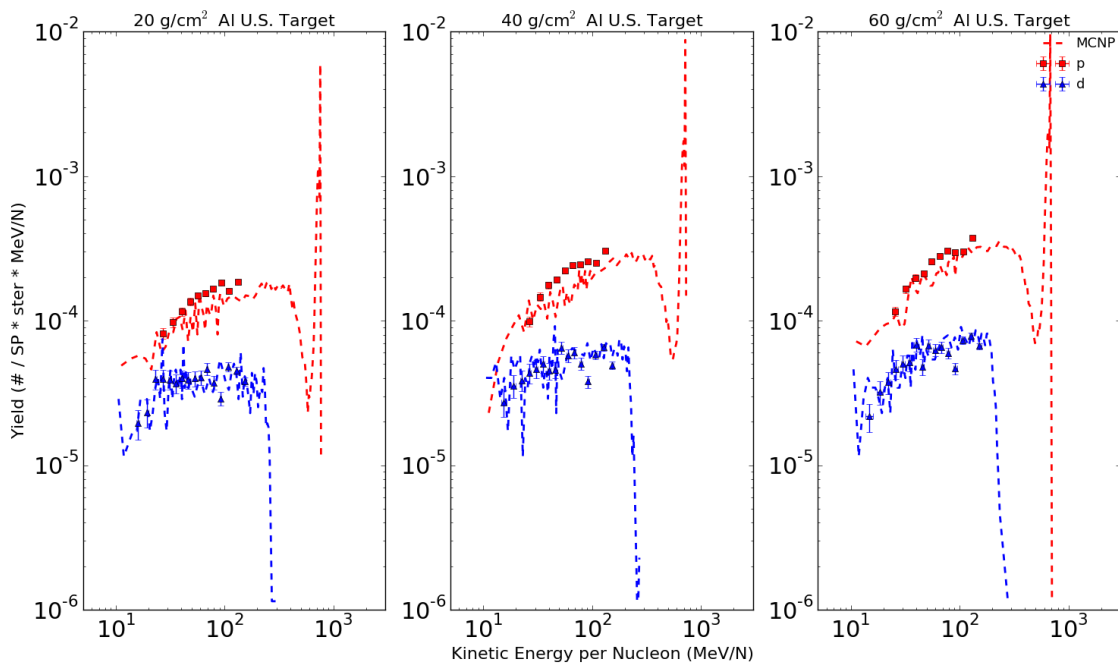


Figure 65. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 800 MeV proton projectiles on aluminum at 10° .

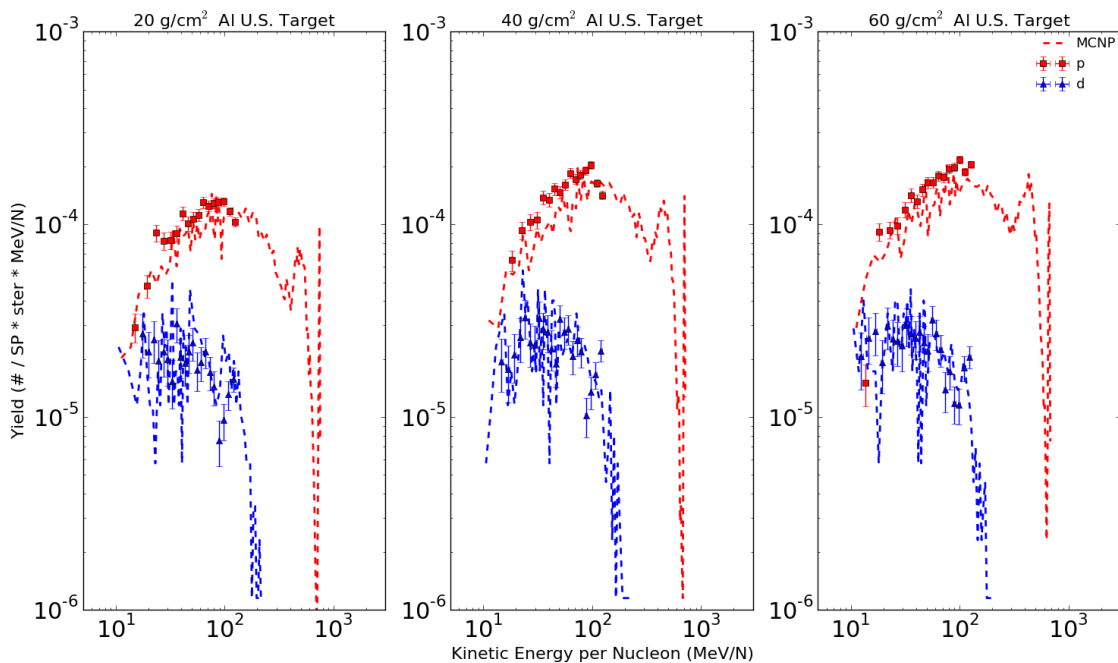


Figure 66. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 800 MeV proton projectiles on aluminum at 30° .

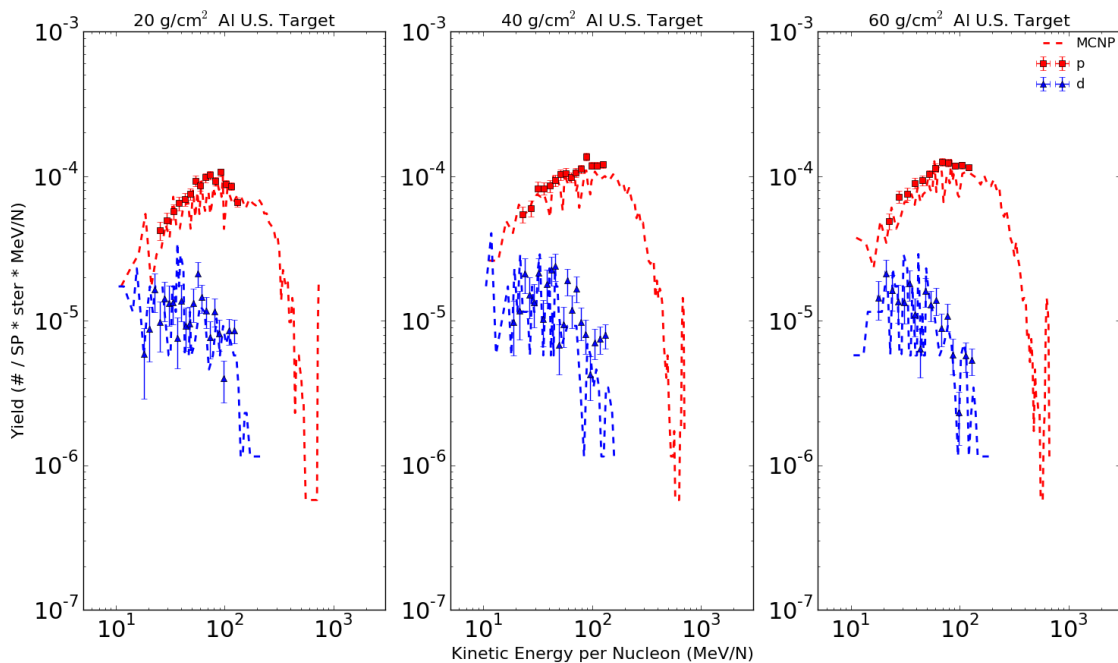


Figure 67. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 800 MeV proton projectiles on aluminum at 45°.

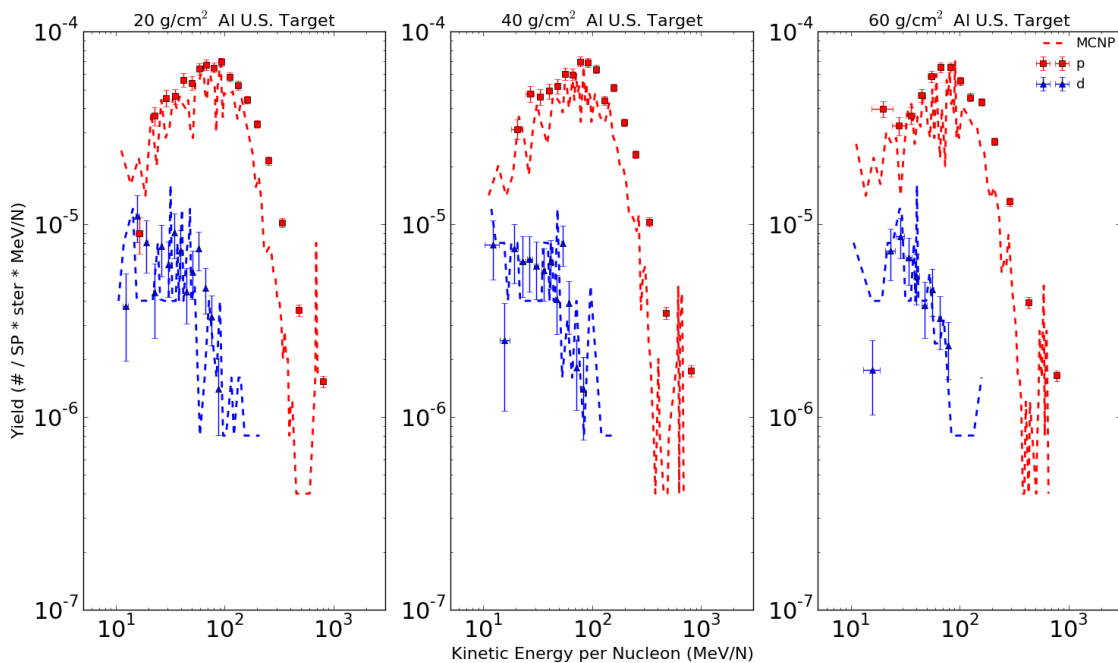


Figure 68. Comparison of MCNP-calculated and experimentally measured DDTT proton and deuteron yields for 800 MeV proton projectiles on aluminum at 60°.

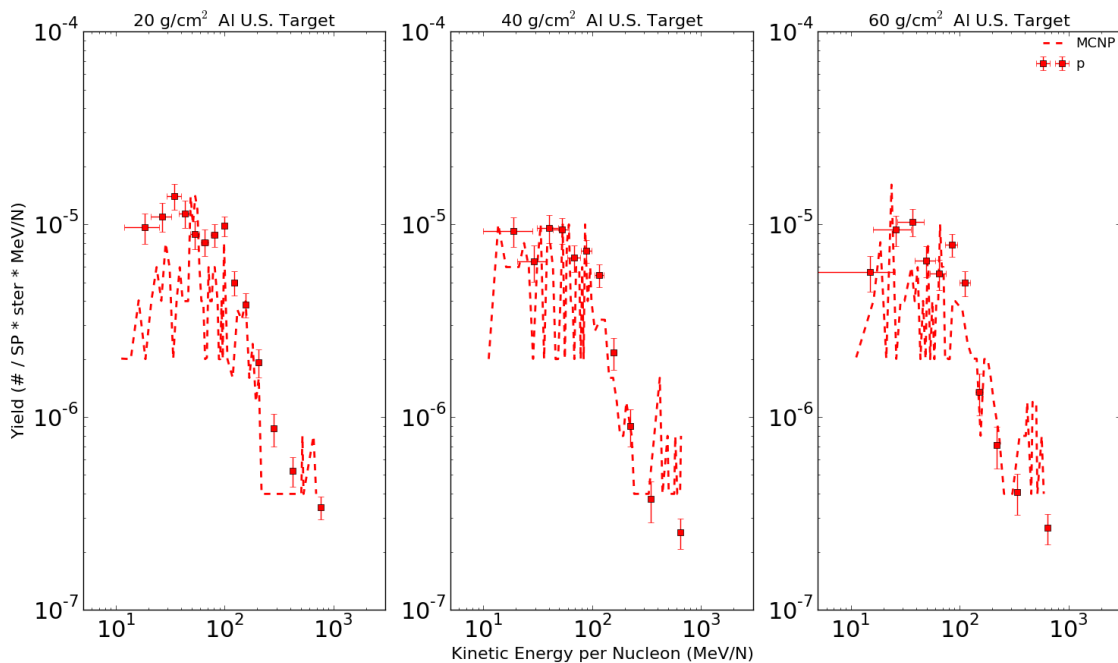


Figure 69. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 800 MeV proton projectiles on aluminum at 80°.

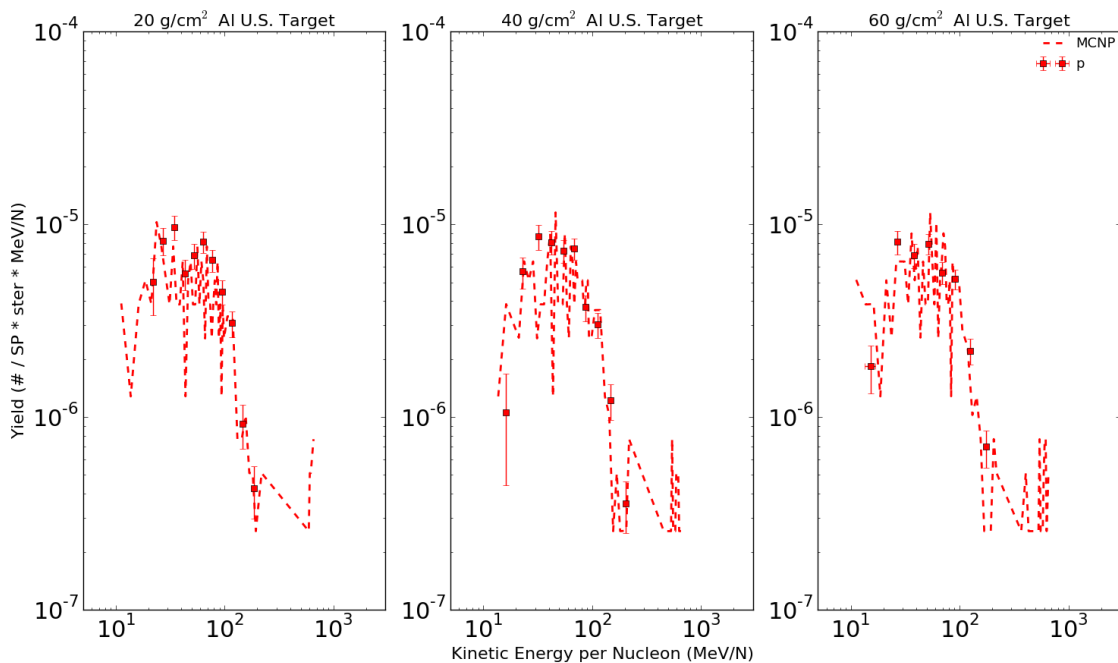


Figure 70. Comparison of MCNP-calculated and experimentally measured DDTT proton yields for 800 MeV proton projectiles on aluminum at 135°.

**Comparisons of experimental double differential thick-target helium isotope
yield data with MCNP simulations**

400 and 800 MeV/N iron projectiles

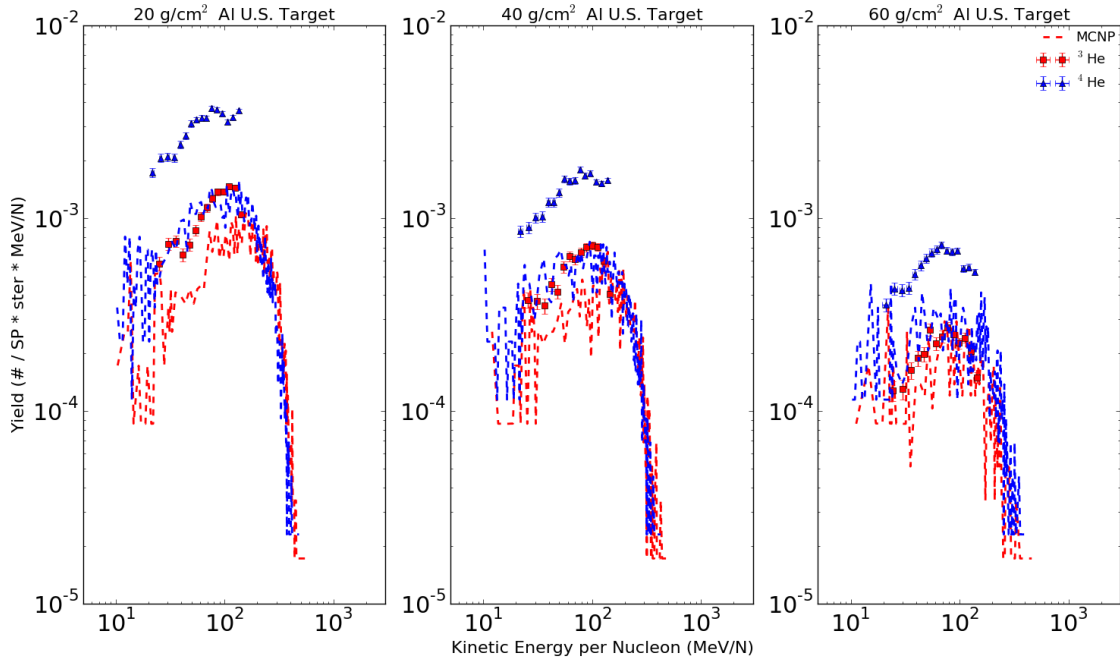


Figure 71. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 and helium-4 yields for 400 MeV/N iron projectiles on aluminum at 10° .

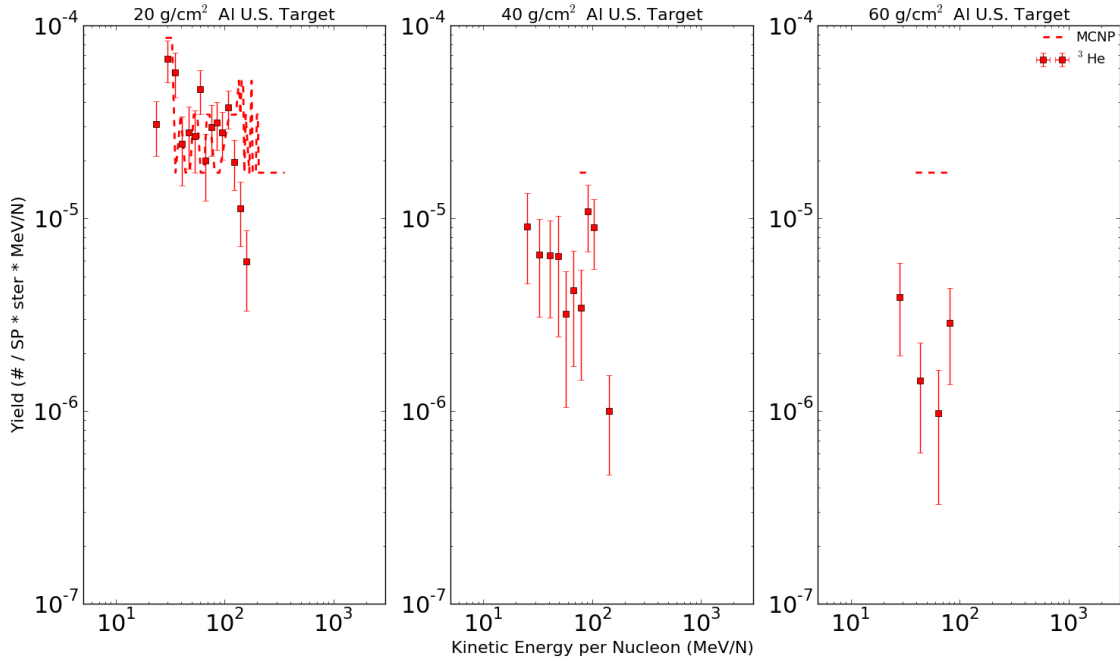


Figure 72. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 yields for 400 MeV/N iron projectiles on aluminum at 30° .

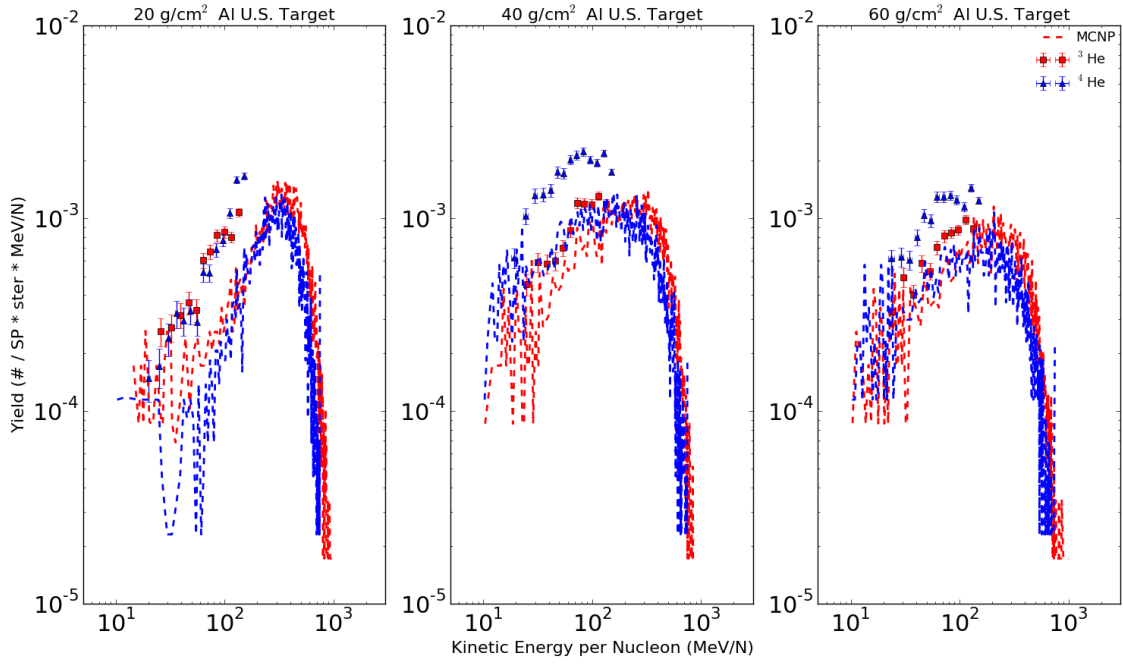


Figure 73. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 and helium-4 yields for 800 MeV/N iron projectiles on aluminum at 10° .

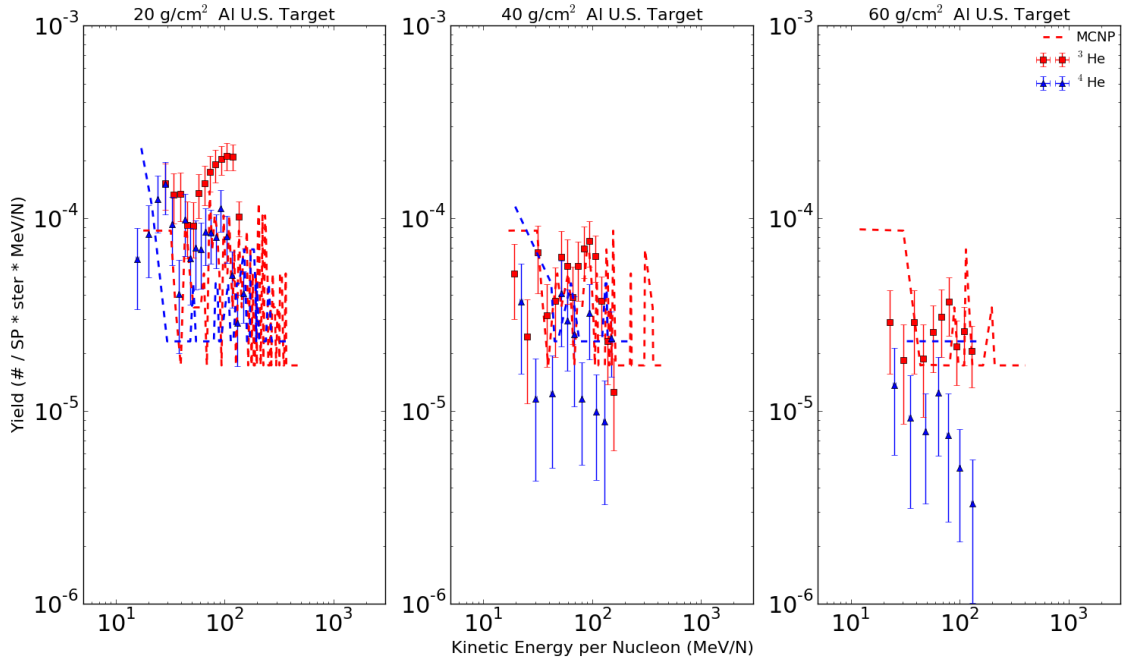


Figure 74. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 and helium-4 yields for 800 MeV/N iron projectiles on aluminum at 30° .

400 and 800 MeV/N helium projectiles

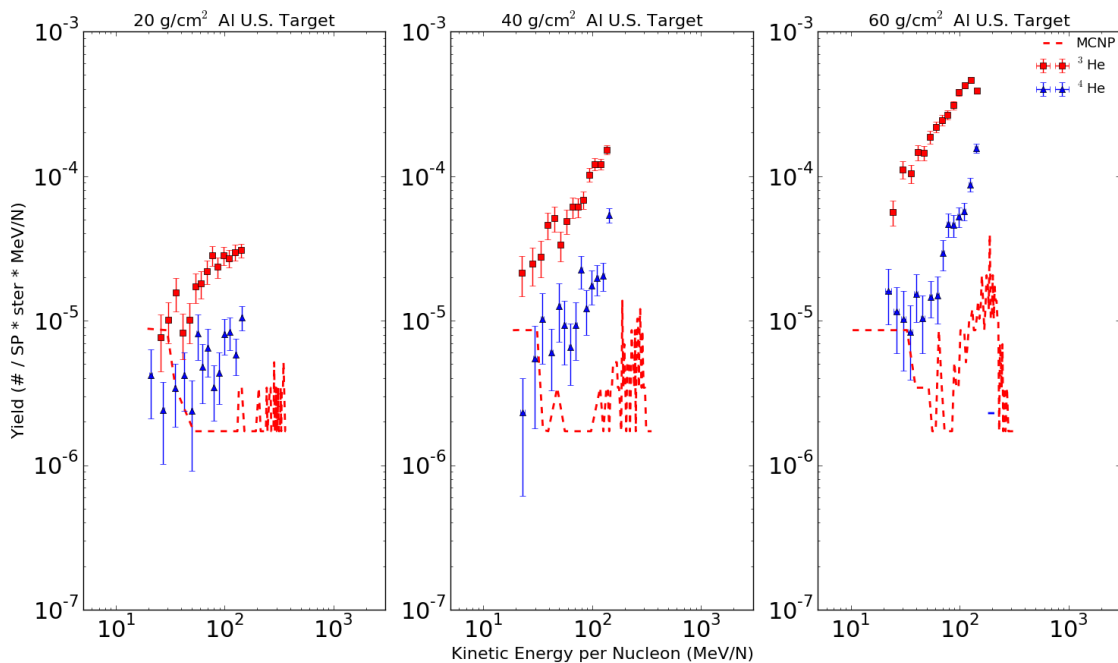


Figure 75. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 and helium-4 yields for 400 MeV/N helium projectiles on aluminum at 10° .

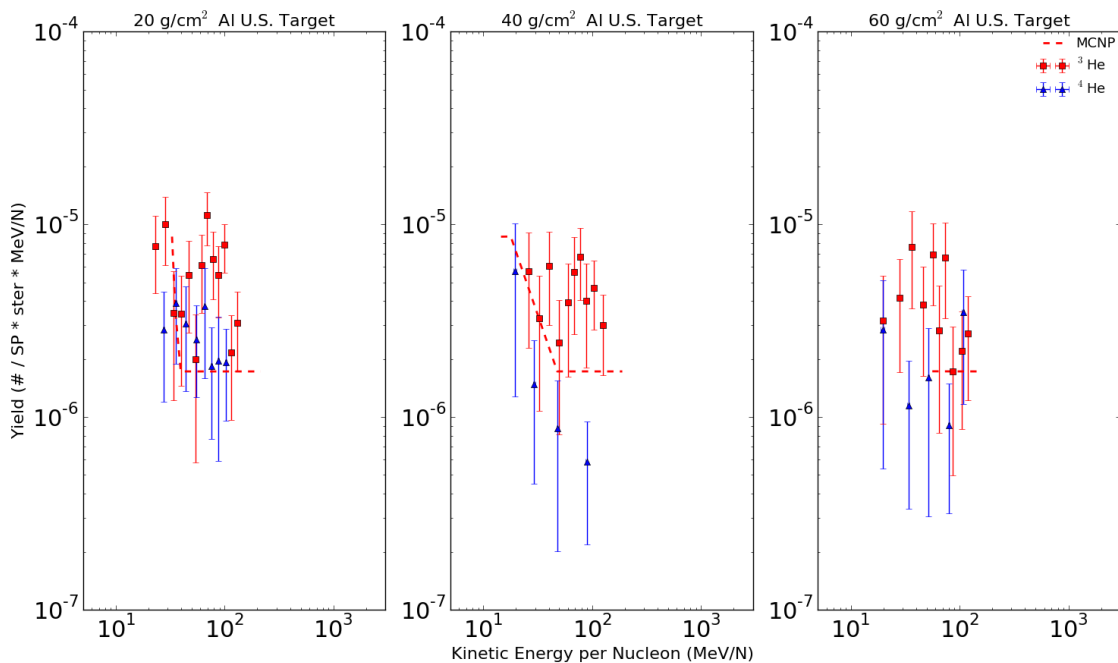


Figure 76. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 and helium-4 yields for 400 MeV/N helium projectiles on aluminum at 30° .

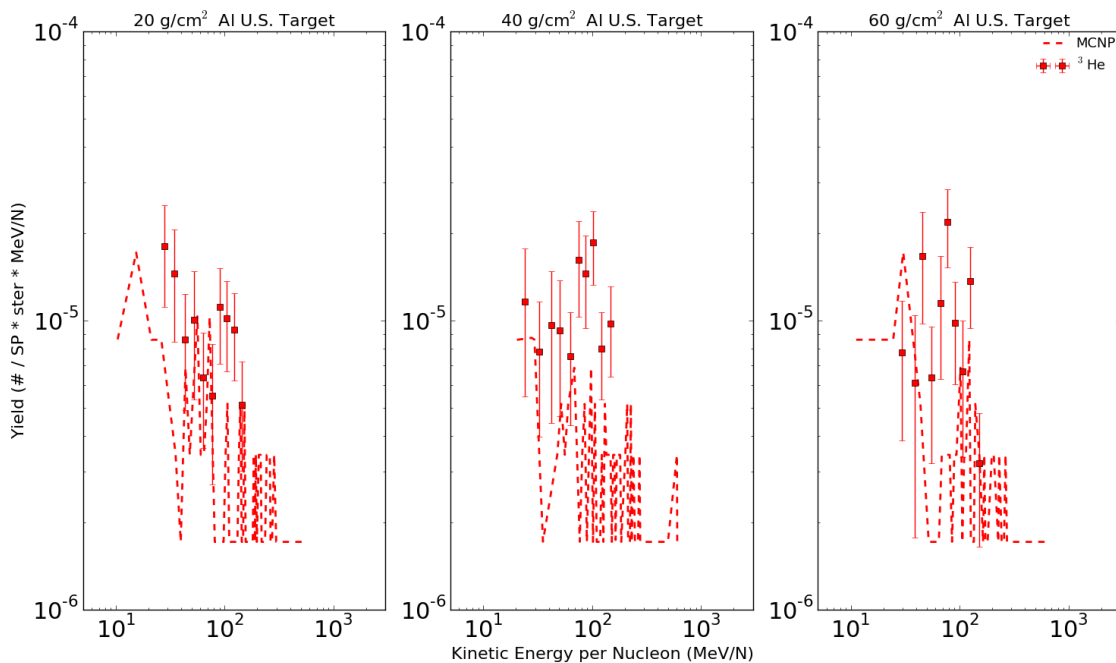


Figure 77. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 yields for 800 MeV/N helium projectiles on aluminum at 10°.

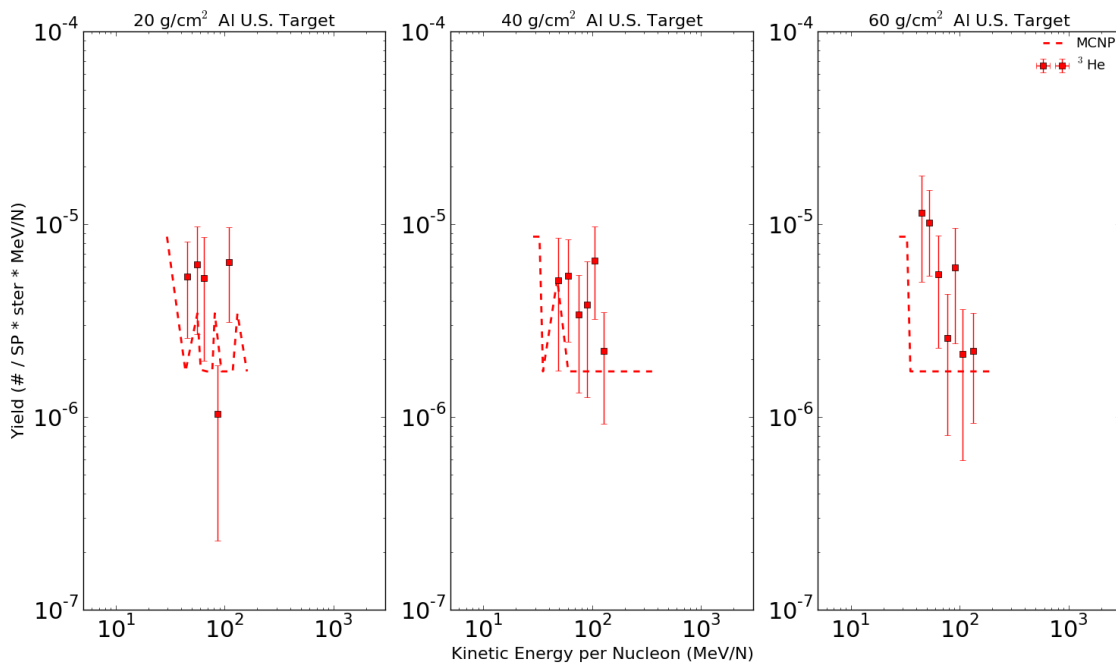


Figure 78. Comparison of MCNP-calculated and experimentally measured DDTT helium-3 yields for 800 MeV/N helium projectiles on aluminum at 30°.

APPENDIX III

**Comparisons of iron- and helium-induced
experimental double differential thick-target proton yield data
with multiple Monte Carlo physics model calculations**

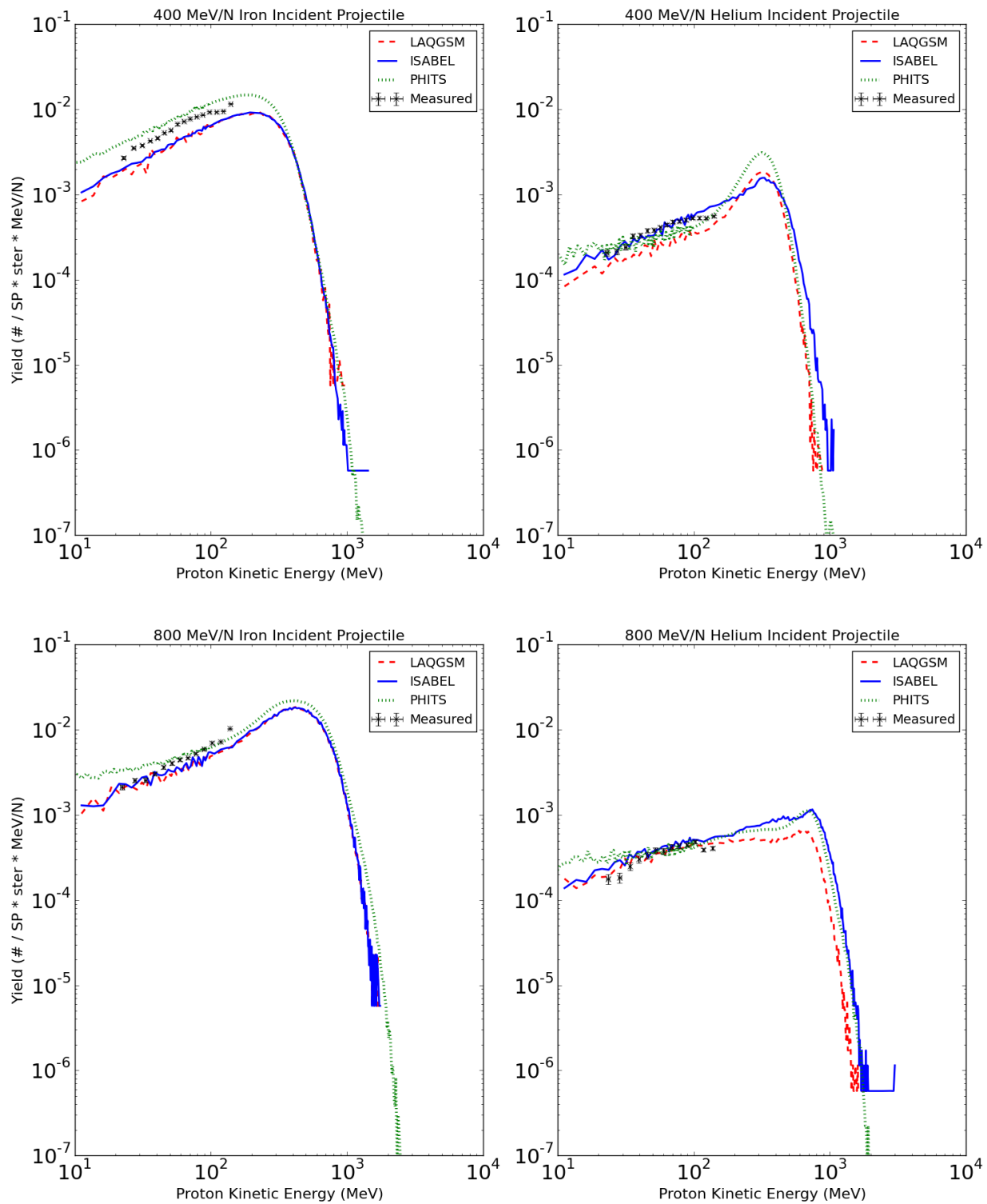


Figure 79. DDTT proton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 10°; multiple Monte Carlo physics model calculations.

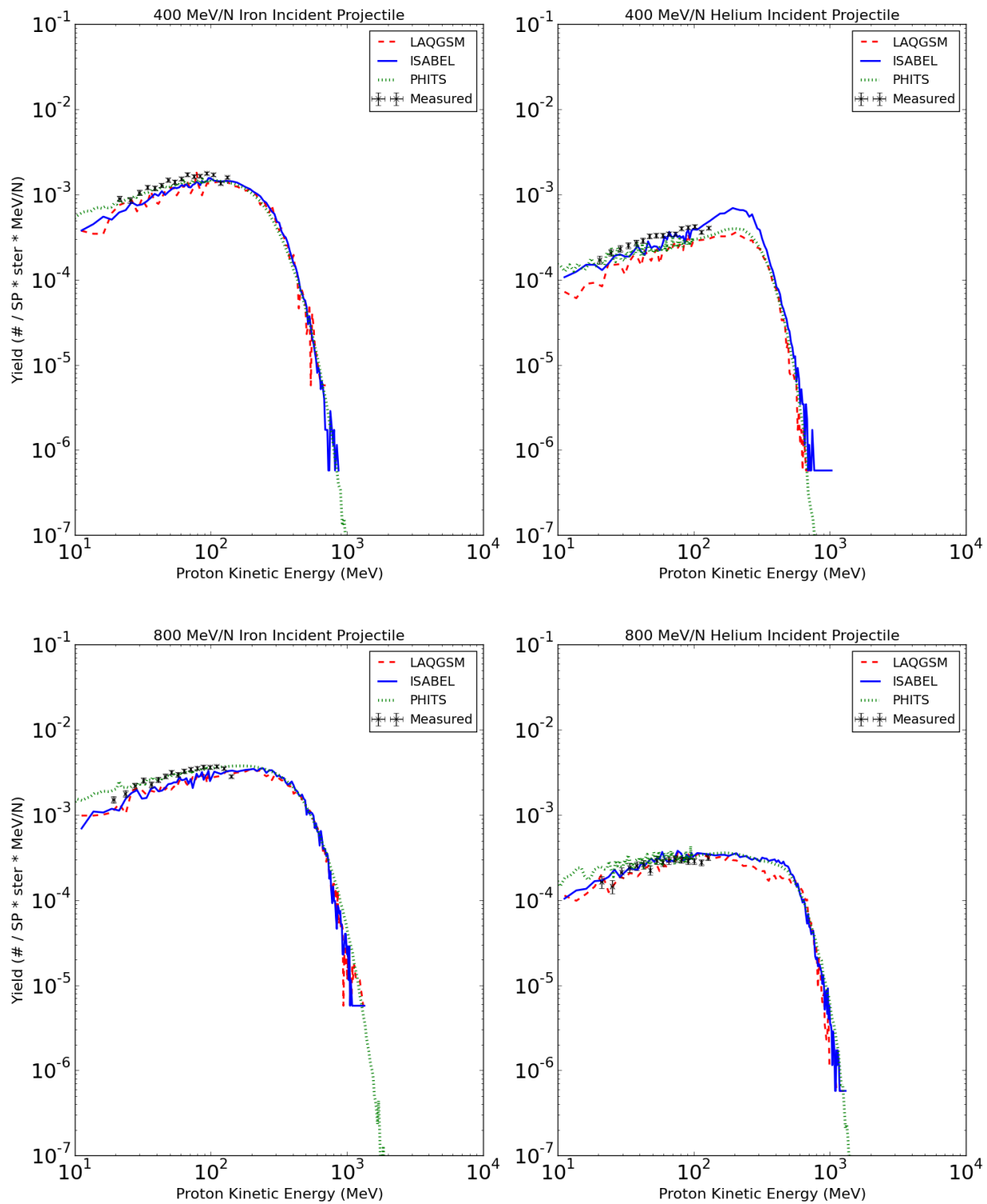


Figure 80. DDTT proton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 30°; multiple Monte Carlo physics model calculations.

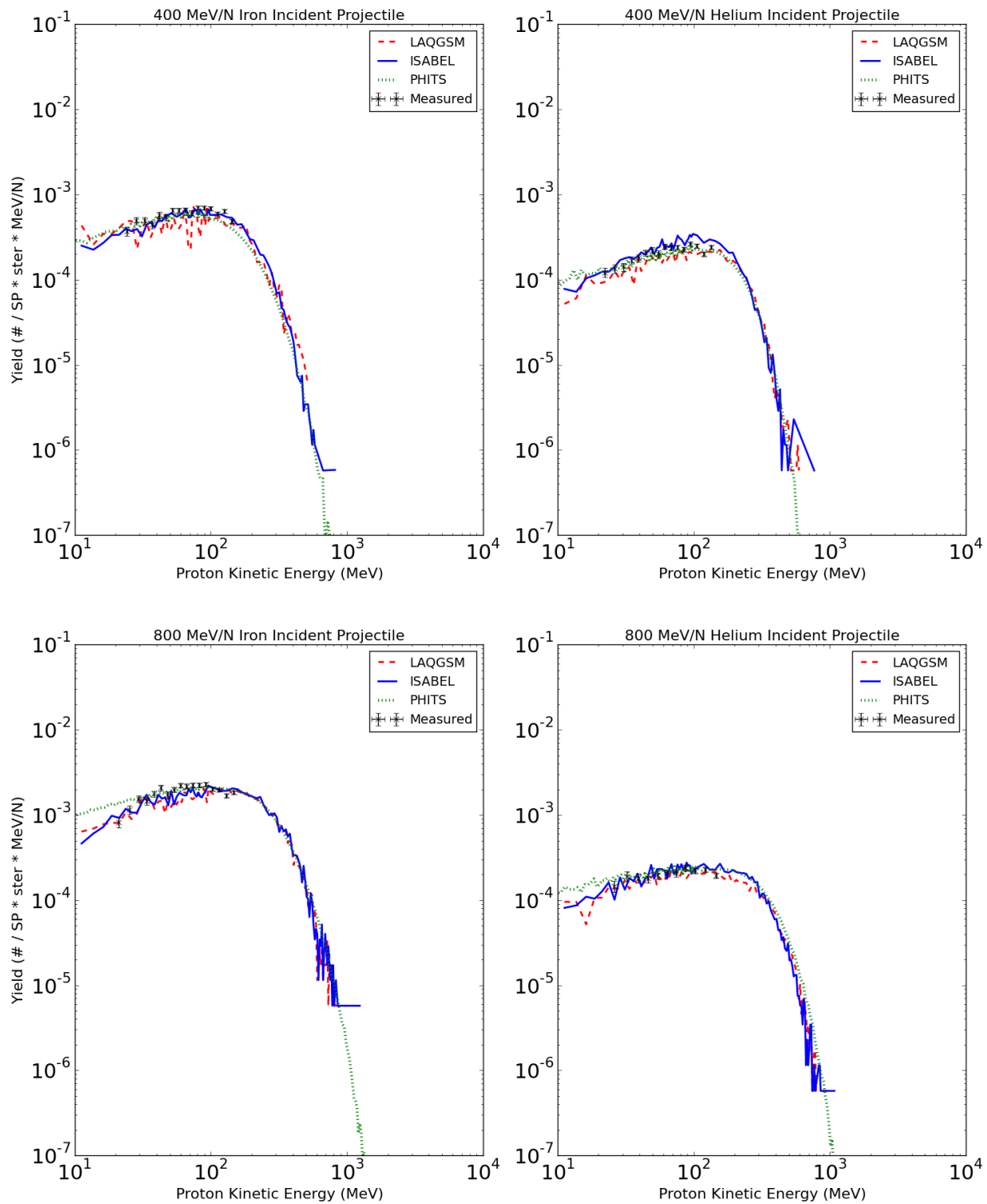


Figure 81. DDTT proton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm^2 aluminum at 45° ; multiple Monte Carlo physics model calculations.

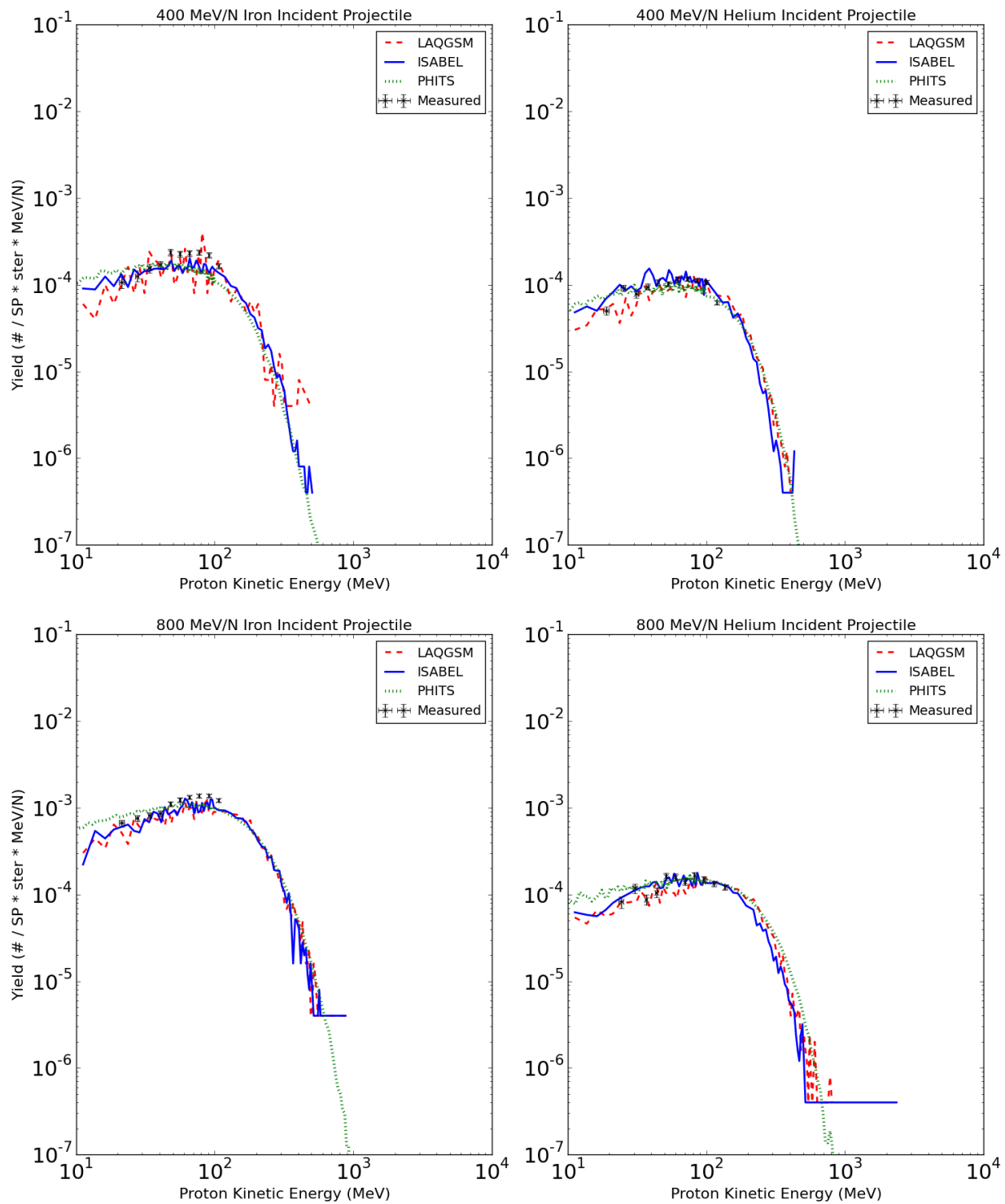


Figure 82. DDTT proton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 60°; multiple Monte Carlo physics model calculations.

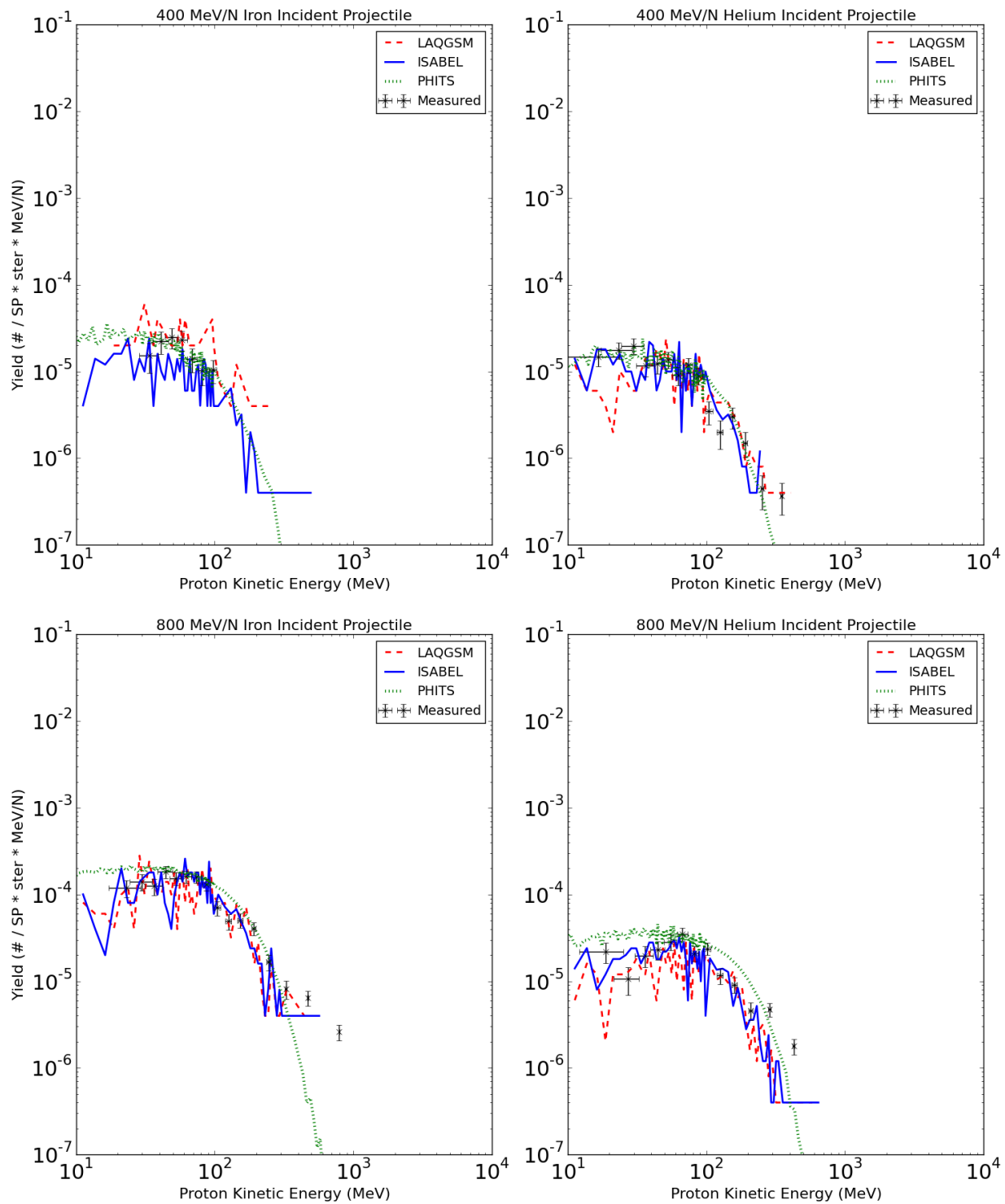


Figure 83. DDTT proton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 80°; multiple Monte Carlo physics model calculations.

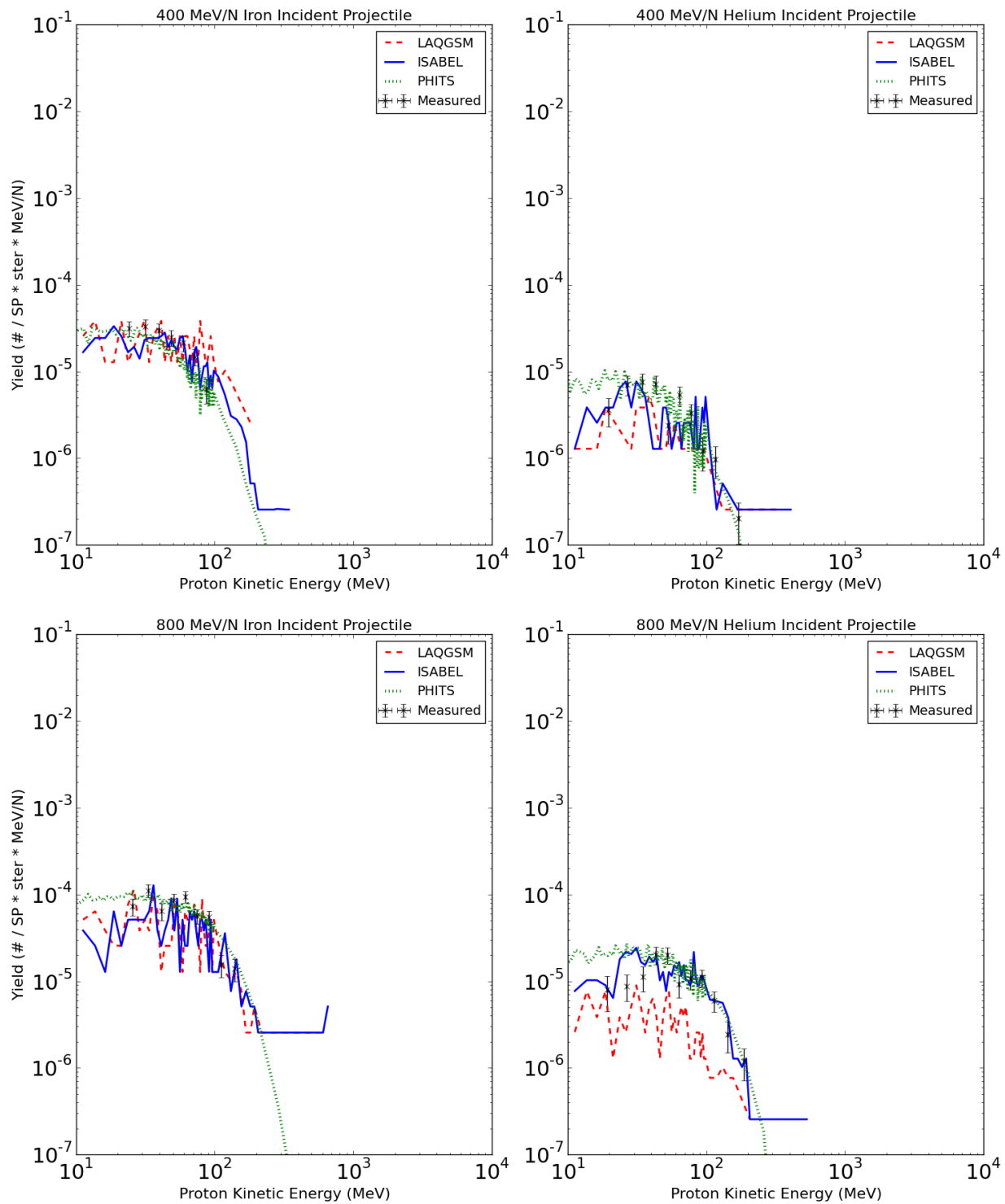


Figure 84. DDTT proton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 135°; multiple Monte Carlo physics model calculations.

**Comparisons of iron- and helium-induced
experimental double differential thick-target deuteron yield data
with multiple Monte Carlo physics model calculations**

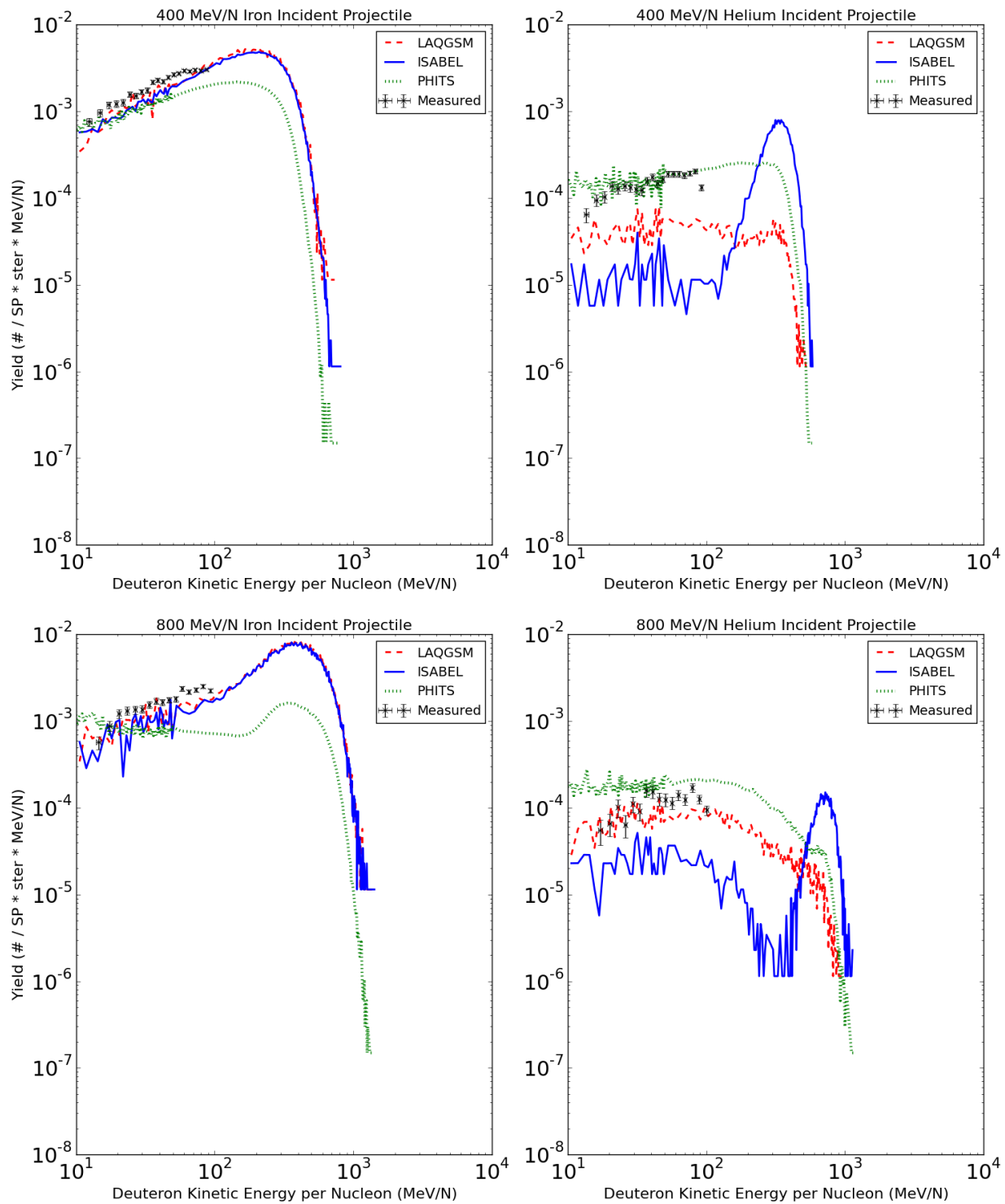


Figure 85. DDTT deuteron yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 10°; multiple Monte Carlo physics model calculations.

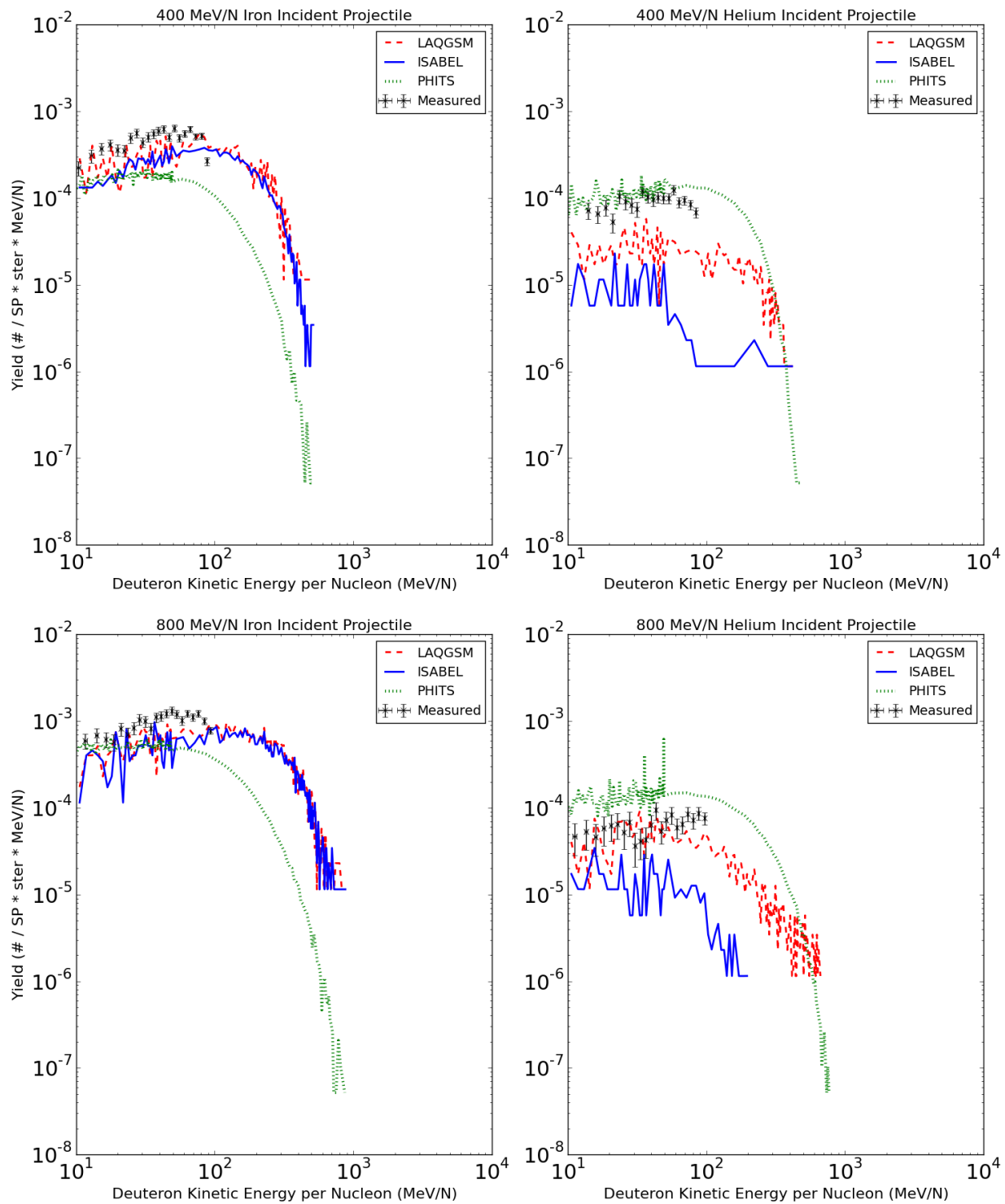


Figure 86. DDTT deuteron yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 30°; multiple Monte Carlo physics model calculations.

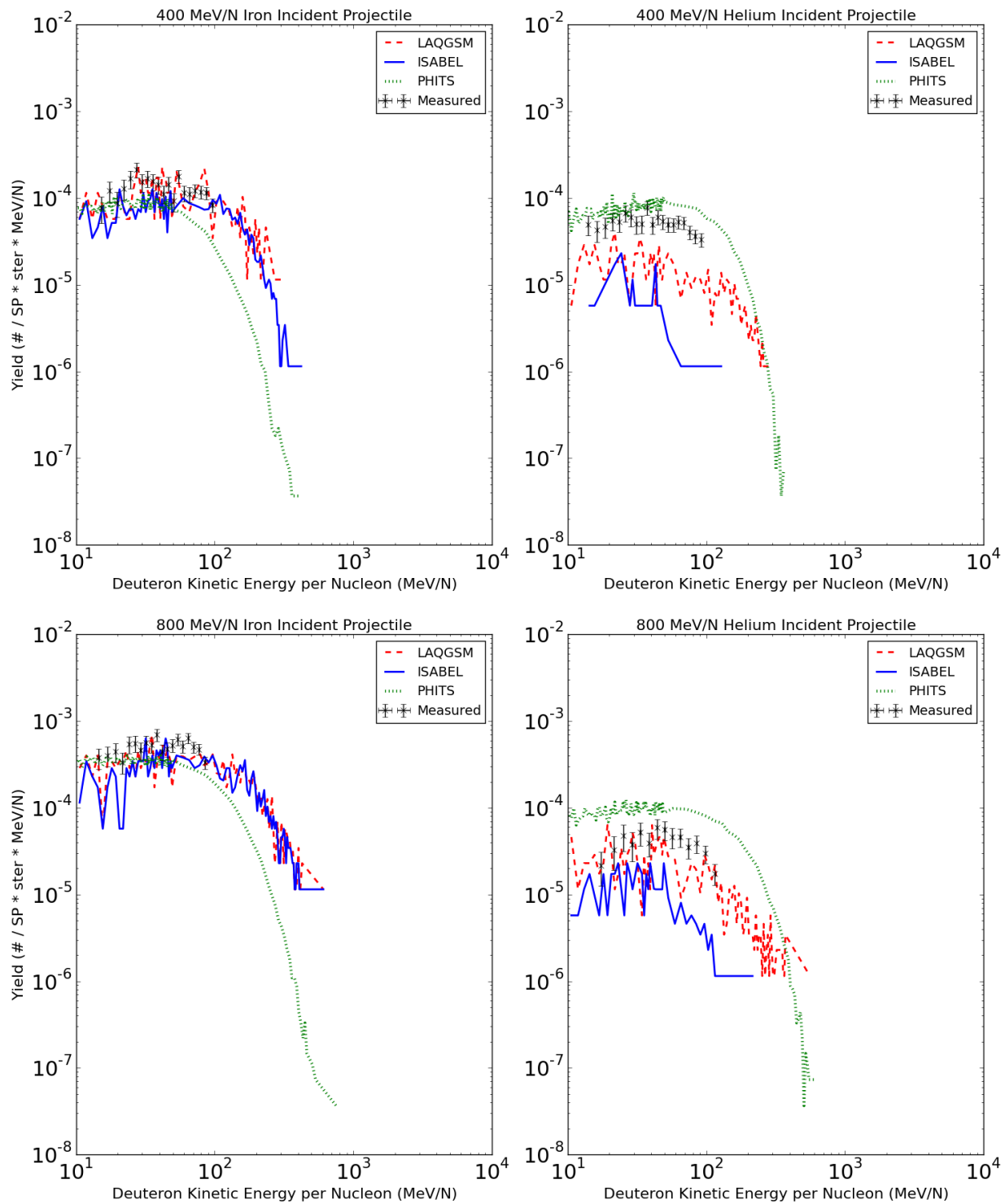


Figure 87. DDTT deuteron yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 45°; multiple Monte Carlo physics model calculations.

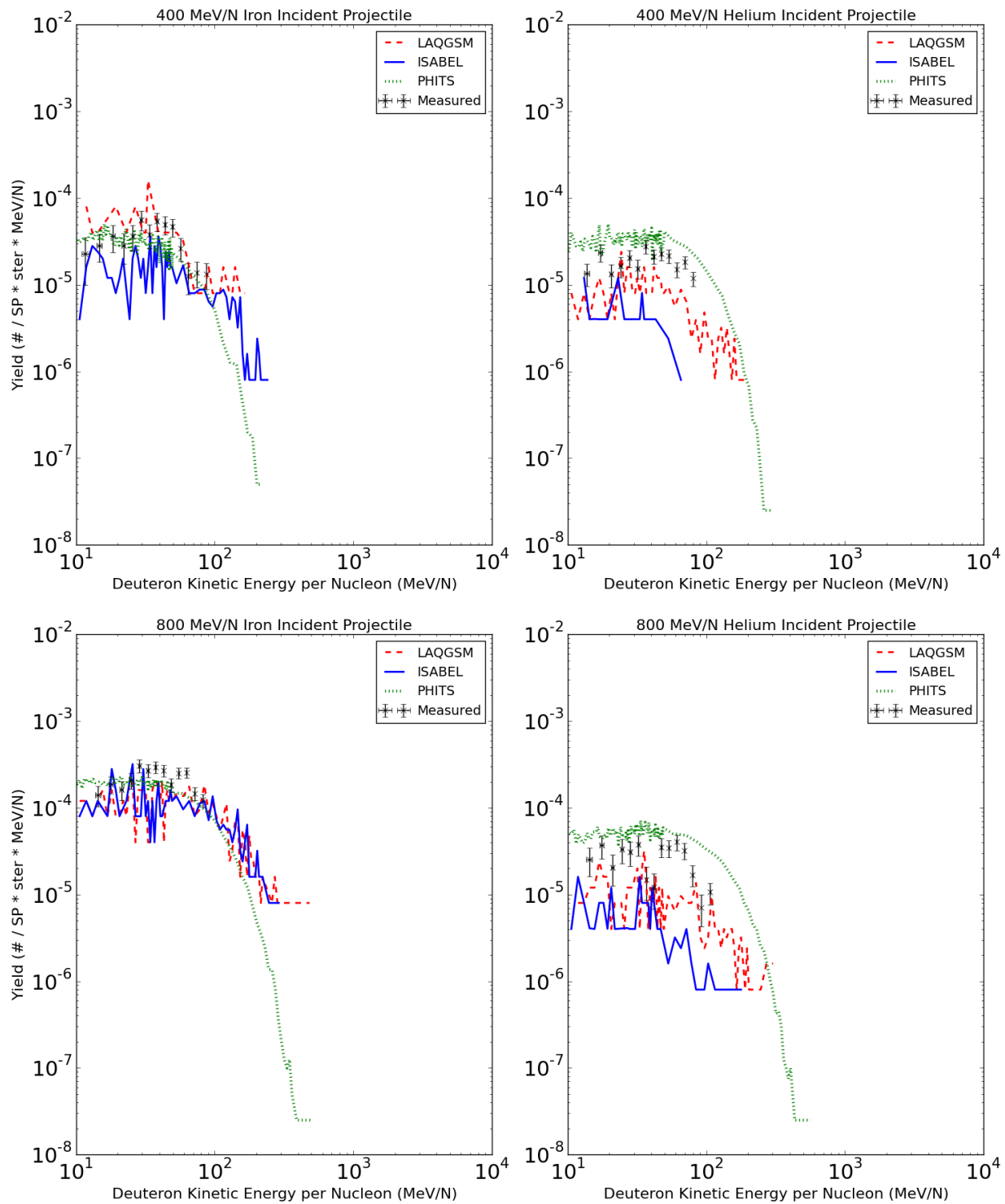


Figure 88. DDTT deuteron yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 60°; multiple Monte Carlo physics model calculations.

**Comparisons of iron- and helium-induced
experimental double differential thick-target triton yield data
with multiple Monte Carlo physics model calculations**

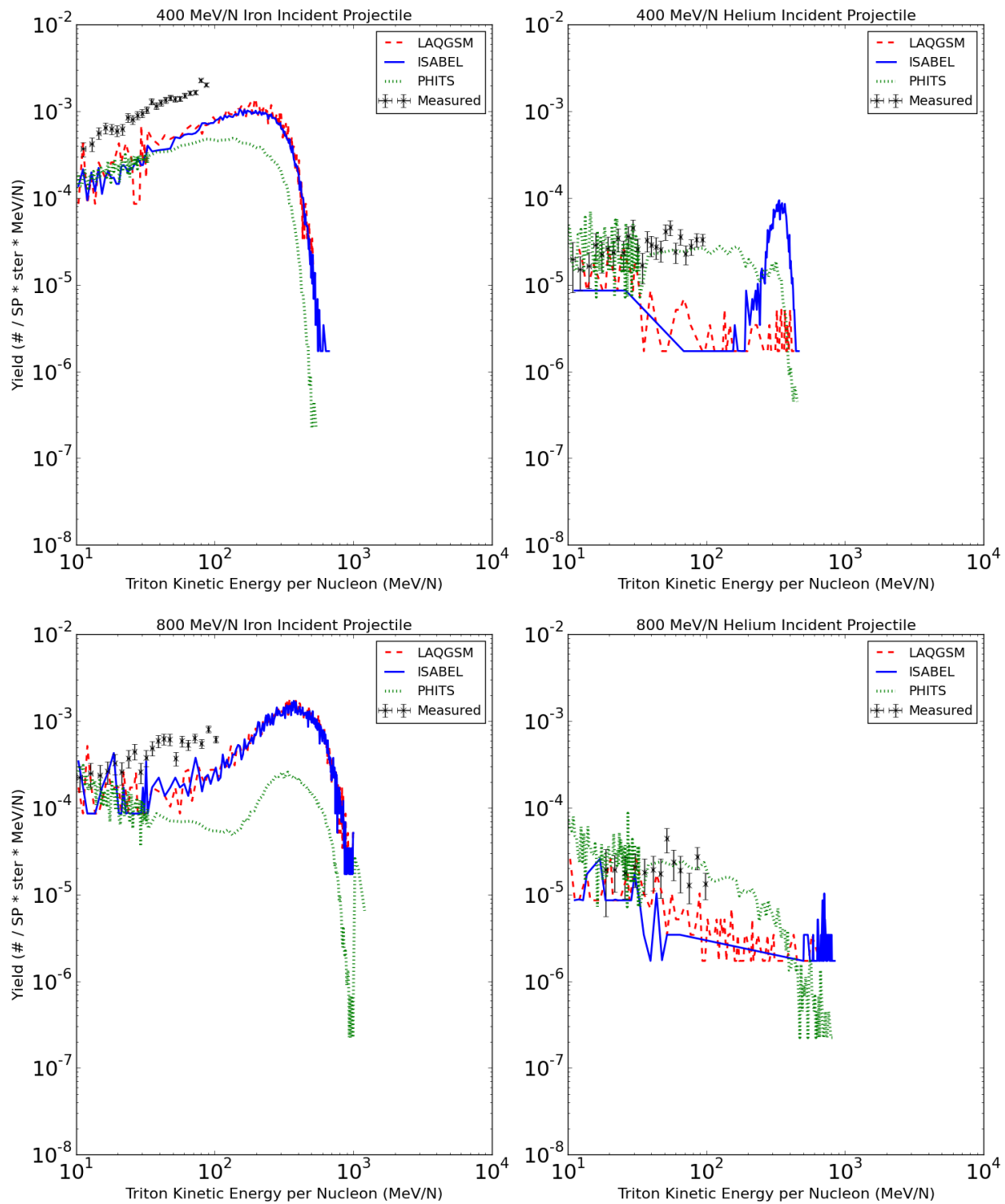


Figure 89. DDTT triton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 10°; multiple Monte Carlo physics model calculations.

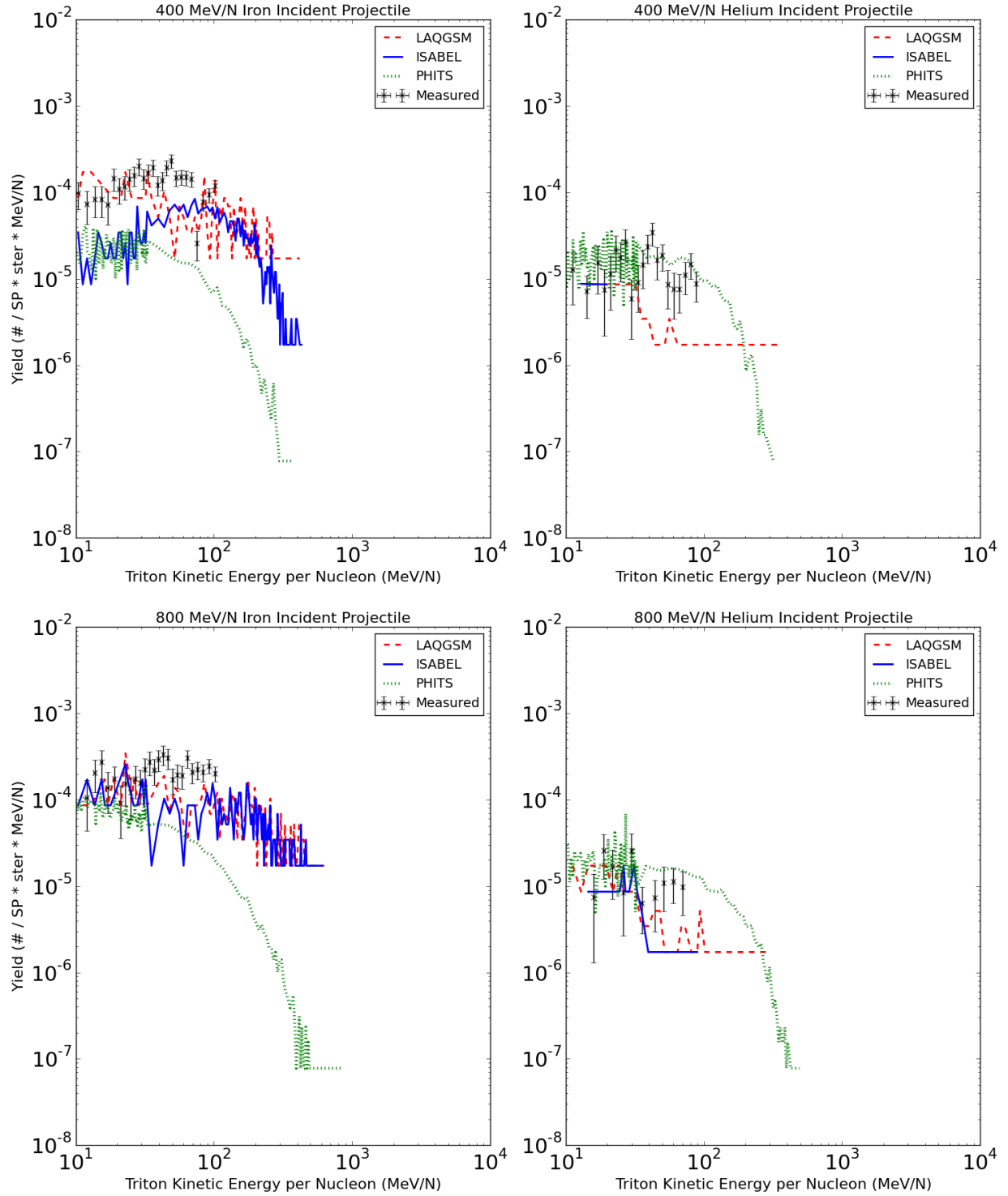


Figure 90. DDTT triton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 30°; multiple Monte Carlo physics model calculations.

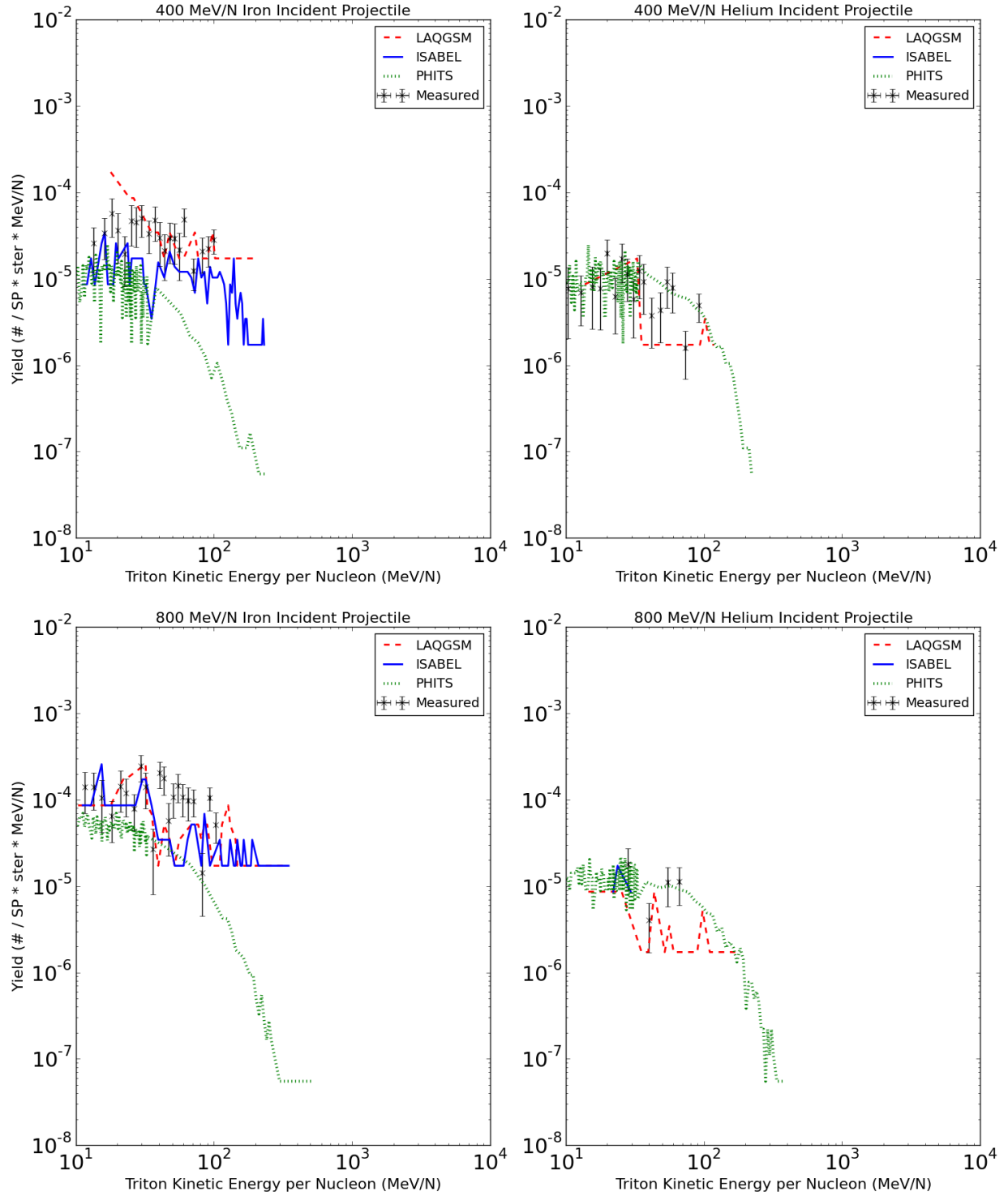


Figure 91. DDTT triton yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 45°; multiple Monte Carlo physics model calculations.

**Comparisons of iron- and helium-induced
experimental double differential thick-target helium-3 yield data
with multiple Monte Carlo physics model calculations**

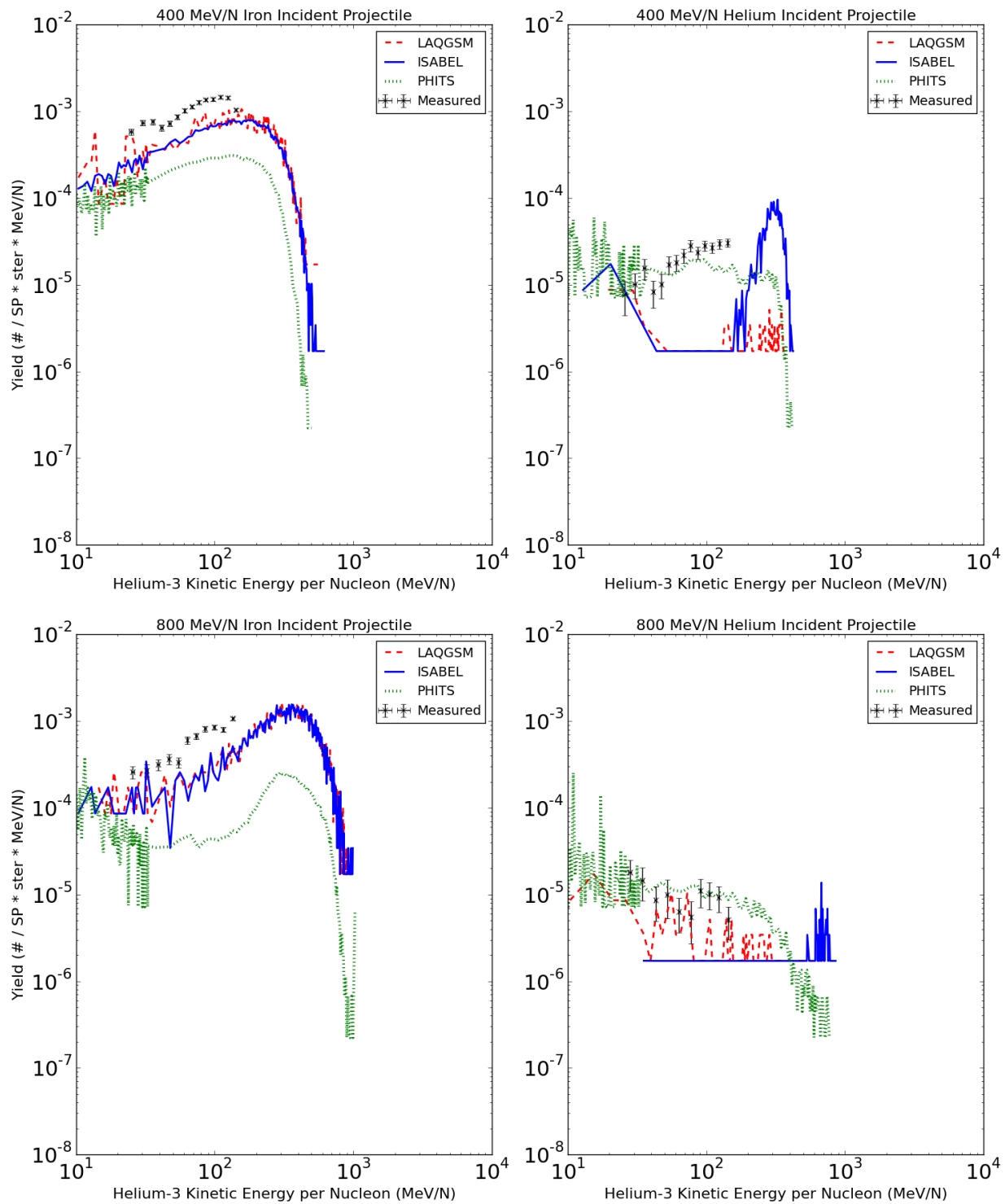


Figure 92. DDTT helium-3 yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 10°; multiple Monte Carlo physics model calculations.

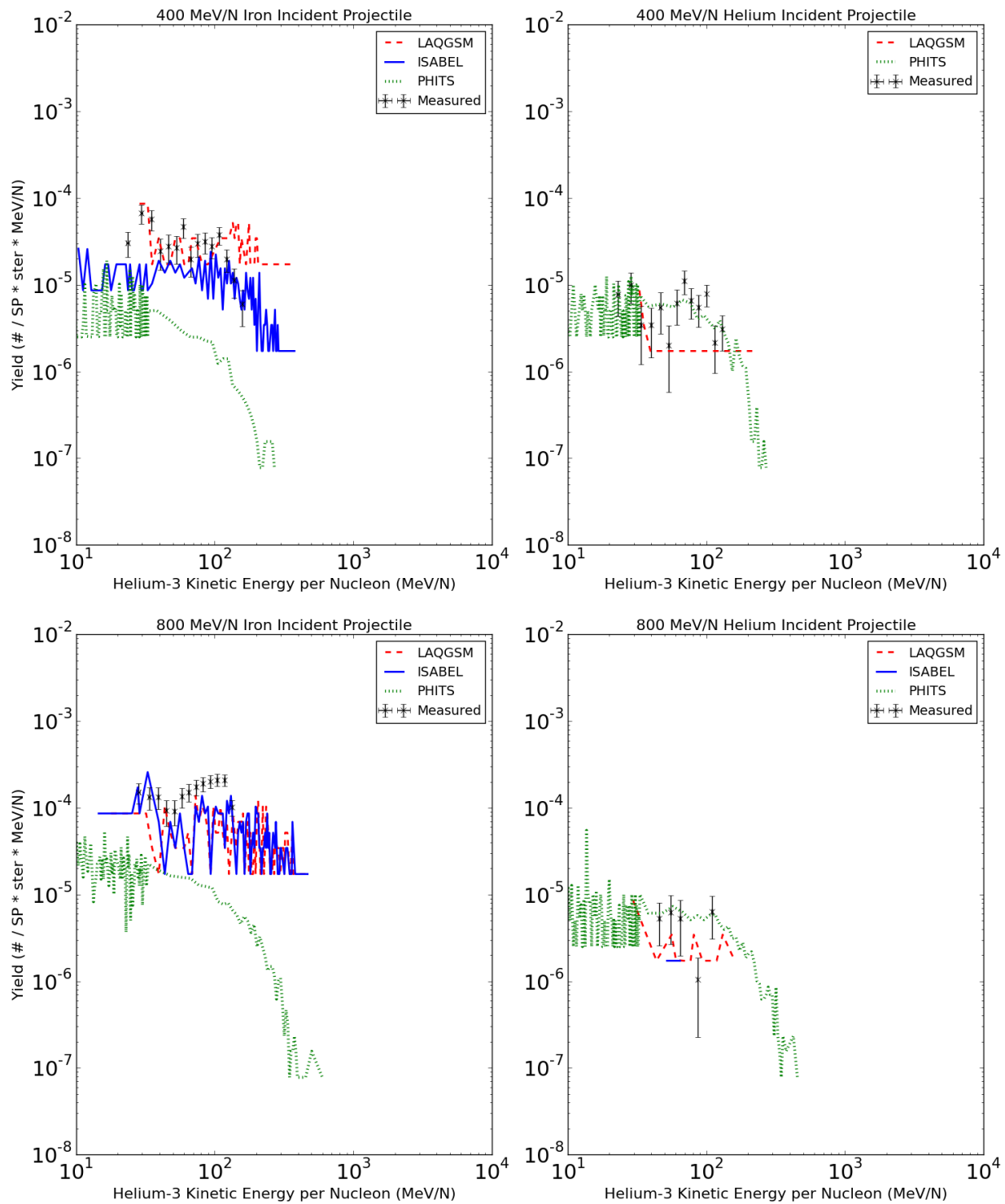


Figure 93. DDTT helium-3 yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 30°; multiple Monte Carlo physics model calculations.

**Comparisons of iron- and helium-induced
experimental double differential thick-target helium-4 yield data
with multiple Monte Carlo physics model calculations**

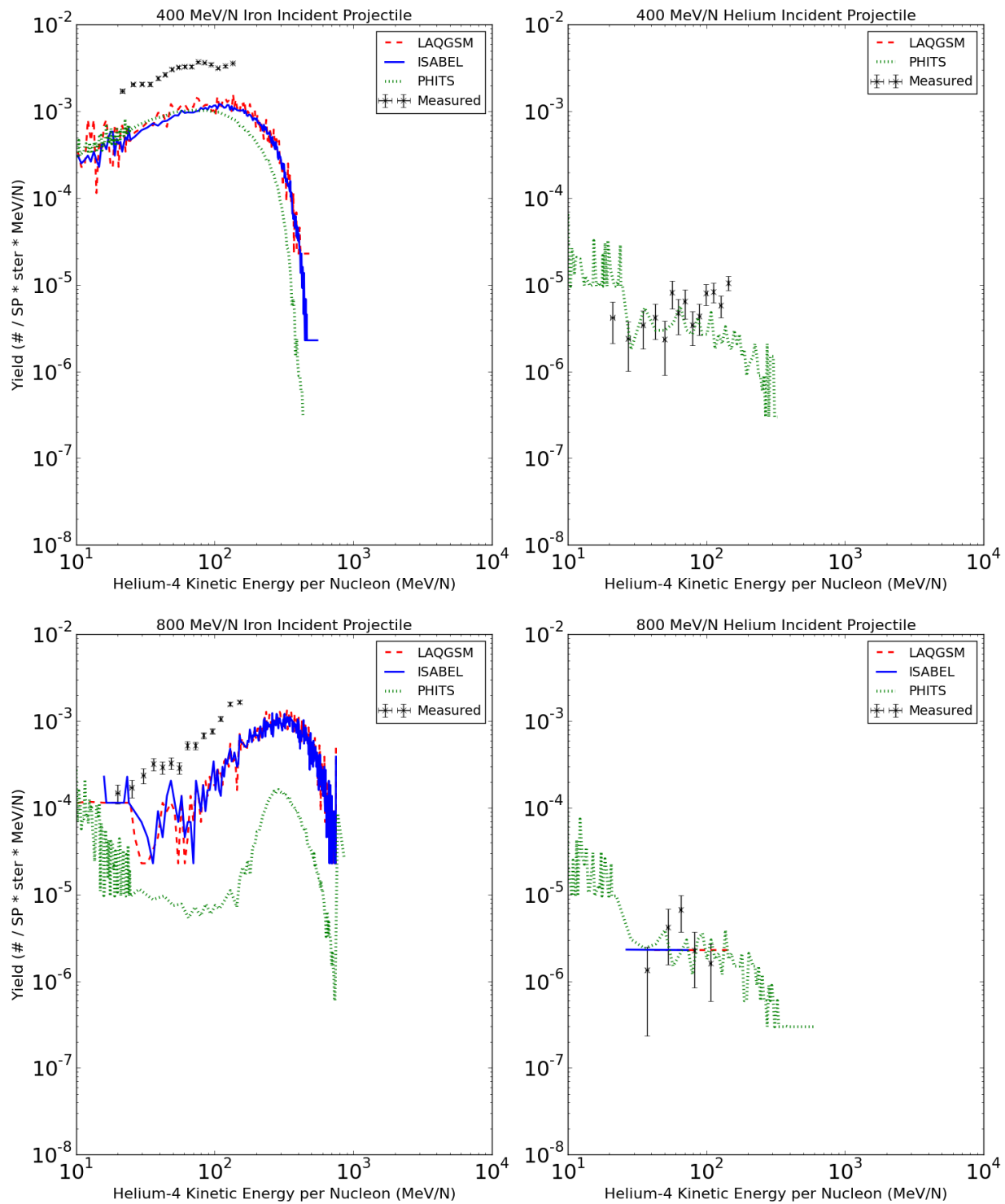


Figure 94. DDTT helium-4 yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 10°; multiple Monte Carlo physics model calculations.

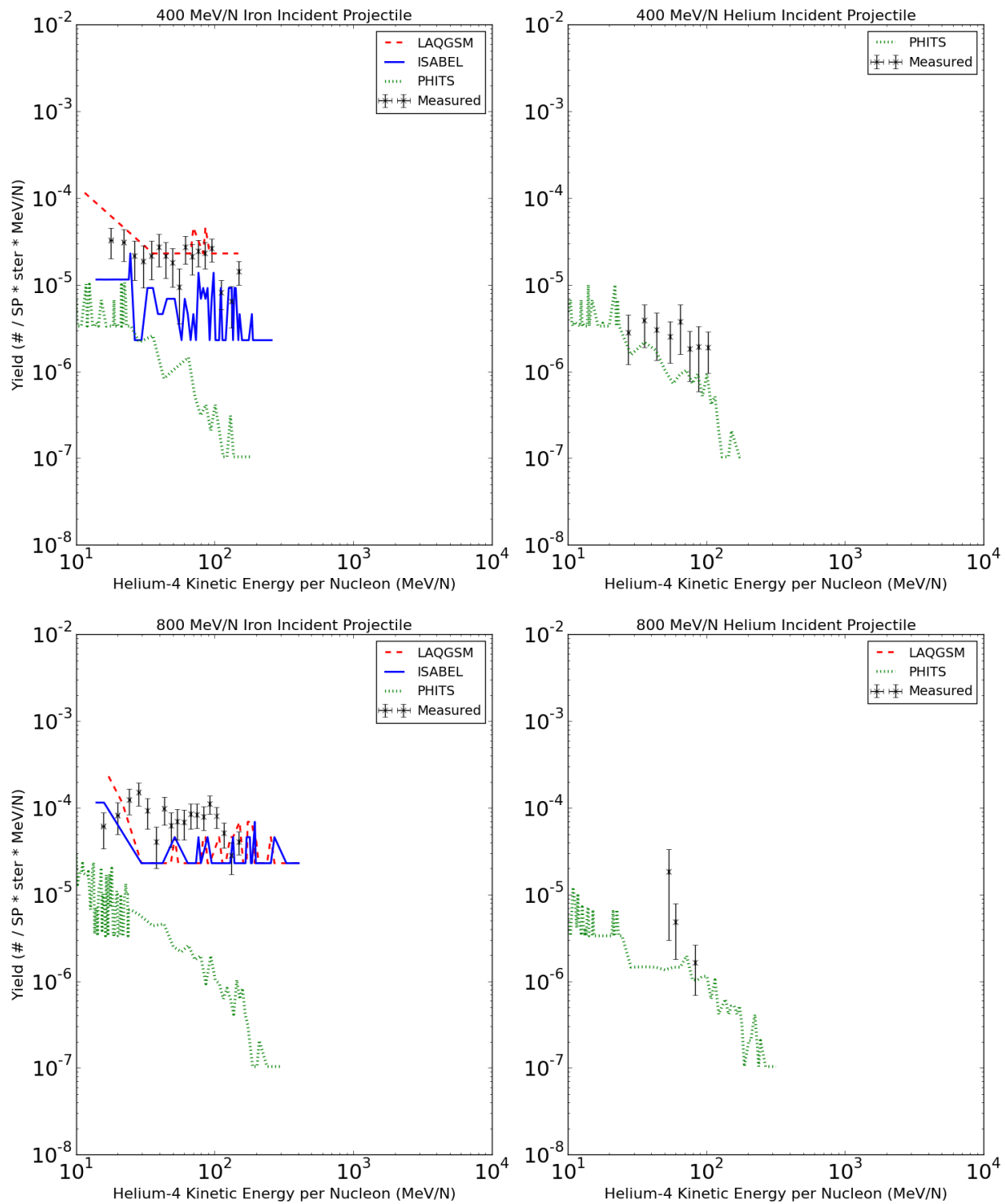


Figure 95. DDTT helium-4 yields for 400- and 800-MeV/N iron and helium projectiles on 20 g/cm² aluminum at 30°; multiple Monte Carlo physics model calculations.

VITA

Luis Antonio Castellanos is from Springfield, VA. He moved to Knoxville to attend the University of Tennessee in 2008. He graduated with his B.S. in Nuclear Engineering with Radiological Engineering Concentration in 2012. In addition to the research presented here, Luis previously worked on spallation target designs for neutron-antineutron oscillation experiments and subcritical reactor applications. After graduating with his Ph.D., he hopes to continue working in the field of the radiation transport as it relates to space exploration applications.