MAECI-MOFFIITS Meeting of the FOOT collaboration of INFN

MAECI = Ministero degli Affari Esteri e della Cooperazione Internazionale
(Ministry of Foreign Affairs and International Cooperation)

MOFFIITS = Measuring Oxygen Fragmentation For Improved Ion Therapy Strategies

FOOT = FragmentatiOn Of Target

INFN = Istituto Nazionale di Fisica Nucleare (National Institute for Nuclear Physics)

Riccione, Italy, May 26 - 28, 2025

NUCLEAR DATA NEEDS FOR PROTECTION FROM SPACE RADIATION

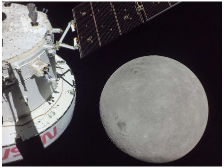
John W. Norbury

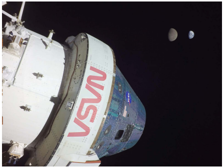
NASA

Monday, May 26, 2025

Outline

Introduction to Space Radiation - Artemis





Images courtesy of NASA

- Artemis I
  - Uncrewed flight test around Moon
    Nov. 16, 2022 - Dec. 11, 2022
- Artemis II
  - Crewed (4) lunar flyby, 2026, 10 days
- Artemis III
  - Human landing near South Pole, 2027
- Artemis IV
  - Lunar space station (Gateway), 2028
- Mars long term plan

INTRODUCTION - SPACEFLIGHT HAZARDS

https://www.nasa.gov/organizations/ochmo/human-spaceflight-hazards/

Geomagnetically trapped radiation

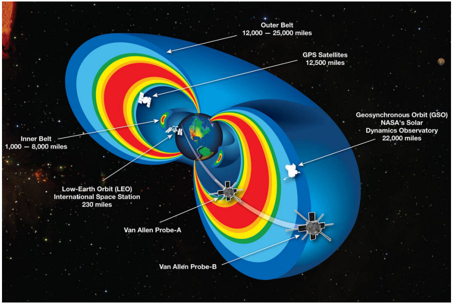
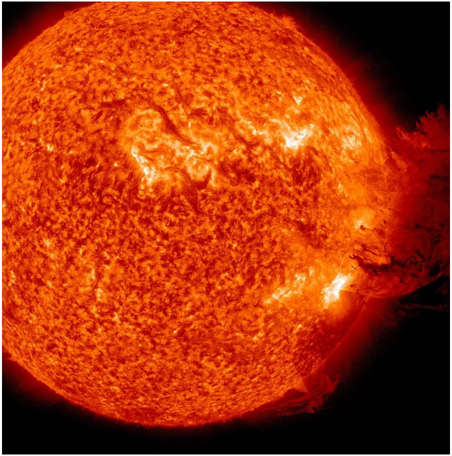


Image courtesy of NASA

- Low energy protons ($<$ 250 MeV) and electrons ($<$ 7 MeV)
- Inner Belt: mostly protons and electrons
- Outer belts: composed of electrons
- Continuous exposure at altitude up to 40,000 km (Geo 36k)
- Can be shielded; mainly relevant to ISS

Slide courtesy of Dr. Charlie Werneth (NASA) & Dr. Shirin Rahmanian (AMA)

Solar Particle Events (SPE)



7 June 2011
Image courtesy of NASA

- Medium (keV to 100s MeV) to high energy protons ($<$ 1 GeV) from coronal mass ejections
- Intermittent exposure with peak activity during solar max
- Can be effectively shielded to prevent severe acute radiation syndrome
- Storm shelters minimize exposure risk

Slide courtesy of Dr. Charlie Werneth (NASA) & Dr. Shirin Rahmanian (AMA)

Galactic Cosmic Rays (GCR)

Crab Nebula

Image courtesy of NASA

- Highly penetrating, complex mixed field including protons and heavier nuclei
- Protons (85%), He ions (12%)
- High charge and energy (HZE) ions (1%) (lower flux but biologically significant)
- Energies $>$ TeV/n
- Chronic low-dose rate exposure that varies with solar cycle
- Difficult to shield due to energy and complexity of field
- Biophysical properties of HZE particles differ vastly from terrestrial radiation with adverse biological affects contributing to health risks
- From supernova shock waves

Slide courtesy of Dr. Charlie Werneth (NASA) & Dr. Shirin Rahmanian (AMA)

- Dose (D)
  - Energy deposited
  - Gray (Gy) (J/kg)
- Dose Equivalent (H)
  - Dose scaled by radiation quality factor (Q)
  - Sievert (Sv)
- Effective Dose:
  - Weighted sum of tissue averaged dose equivalent
  - Tissue weights: radiosensitivity of specific tissues
  - Sievert (Sv)
- NASA Career Permissible Exposure Limit (PEL)
  - Exposure should not exceed effective dose of 600 mSv
  - Corresponds to mean Risk of Exposure Induced Death (REID) for cancer mortality of 3% for 35 yr old female

Introduction - Terrestrial exposures

Exposure Scenario	Dose (mGy)
Chest x-ray	0.1-0.23
Computed tomography-Chest	20-30
Computed tomography-Full body	50-100
Cardiac catheterization	12-40
Mammogram	0.6-2.9

Cancer Radiotherapy to tumor: doses ≥ 20 Gy

Department of Energy Ionizing Radiation Dose Ranges Charge (2017)

Slide courtesy of Dr. Charlie Werneth - NASA

Introduction - Space radiation exposures

Exploration Mission	Mission Duration	Dose (mGy)	Dose Equivalent (mSv)[a]
ISS in LEO	6 months	30-60	50-100
ISS in LEO	1 year	60-120	100-200
Sortie to Gateway (free space)	30 days	20	55
Lunar surface mission (2 weeks on surface)	42 days	25	70
Sustained lunar operations	1 year	100-120	300-400
Deep space	1 year	175-220	500-650
Mars mission	650 to 920 days	300-450	870-1200

[a]Both NASA defined quality factors and ICRP 60 quality factors considered in range of estimates

Simonsen LC, Slaba TC, Guida P, Rusek A (2020) NASA's first ground-based Galactic Cosmic Ray Simulator: Enabling a new era in space radiobiology research. *PLoS Biol* 18(5): e3000669. https://doi.org/10.1371/journal.pbio.3000669

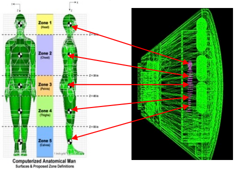
Slide courtesy of Dr. Charlie Werneth - NASA

Note: Previous slide PEL was Effective Dose, not Dose Equiv.

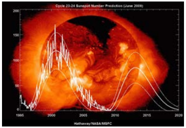
Introduction - Space radiation mitigation

- Radiation shielding
- Mission planning: time in solar cycle and mission duration
- Crew selection: age, previous exposure
- Biomarkers predictive of radiation induced diseases
- Physical activity: studies indicate reduced cancer incidence

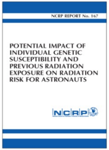
Shield Design and Optimization



Variations in Solar Cycle



Individual Sensitivity


NCRP REPORT No. 167

POTENTIAL IMPACT OF INDIVIDUAL GENETIC SUSCEPTIBILITY AND PREVIOUS RADIATION EXPOSURE ON RADIATION RISK FOR ASTRONAUTS

NCRP

Exercise and Conditioning

Slide courtesy of Dr. Charlie Werneth - NASA

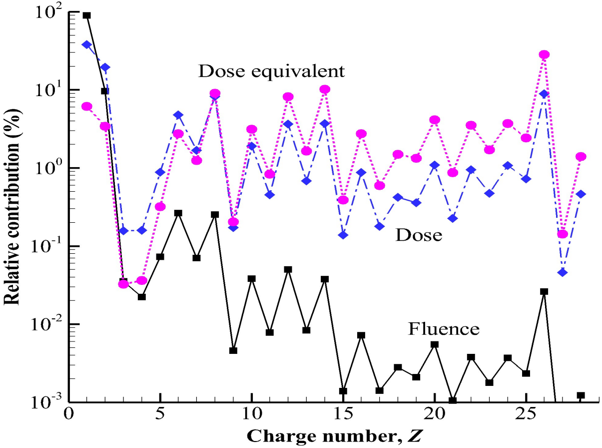
Introduction - Space radiation health risks

- **Risk of radiation carcinogenesis**
  - Morbidity and mortality risks
- **Risk of acute and late central nervous system (CNS) effects**
  - Changes in motor function and behavior or neurological disorders
- **Circulatory diseases**
  - Heart and Vasculature
- **Risk of acute radiation syndromes**
  - Prodromal effects (nausea, vomiting, anorexia, and fatigue), skin injury, and depletion of blood forming organs

Slide courtesy of Dr. Charlie Werneth - NASA

Relative contribution to fluence, dose, dose equivalent

First 4 peaks: H, He, C, O (Average over 1 year during solar min behind 5 g/cm^2 Aluminum)



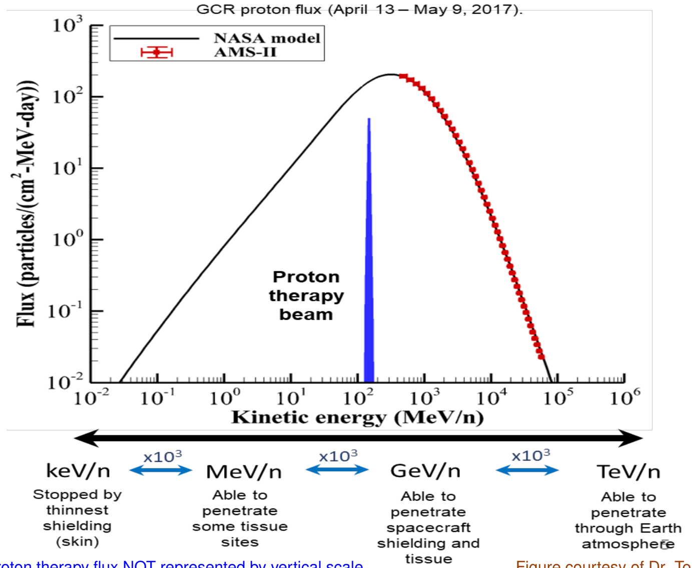
GCR environment during solar minimum conditions (June 1976) - Badhwar-O'Neill 2010 GCR model

Simonsen, Slaba, Guida, Rusek, PLOS Biology 18(5): e3000669, 2020 [Open Access]

Figure easily mis-interpreted: Looks like Fe very important, but note very thin shield 5 g/cm^2

But Fe fragments into light ions & neutrons before reaching astronaut - *more details later*

SPACE RADIATION & ION THERAPY OVERLAP



Note: Proton therapy flux NOT represented by vertical scale

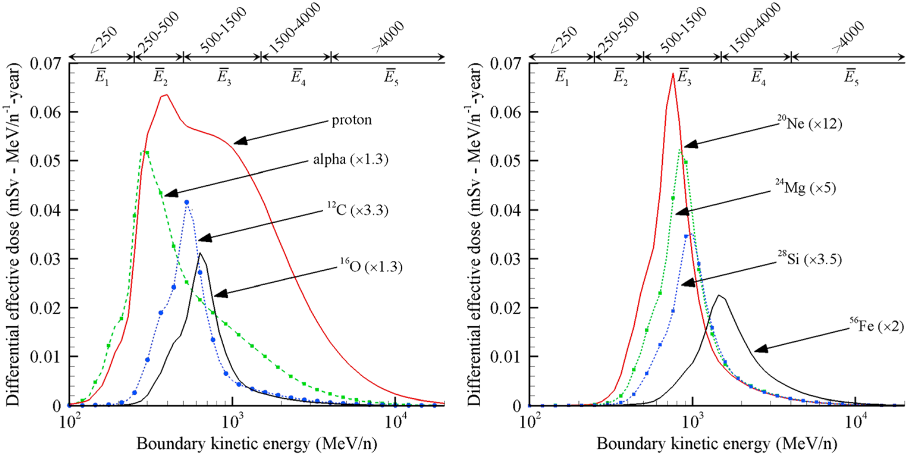
Figure courtesy of Dr. Tony Slaba

AMS = Alpha Magnetic Spectrometer

Effective dose contributions versus GCR BOUNDARY (incident) energy

(20 g/cm^2 Aluminum)

Proton, ^{4}He (alpha), ^{12}C, ^{16}O peaks $\sim$ ion therapy energies



Slaba & Blattnig, Space Weather 12, 217, 2014

Space Radiation & Ion Therapy overlap

Common needs:

- Uncertainty Quantification (UQ)
- Cross section measurements overlap
  - Similar types (double-differential)
  - Similar projectiles (H, He, C, O) space rad needs additional
  - Similar projectile energies space rad also needs additional
  - Similar targets space rad also needs additional
  - Similar fragments (light ions)
- Nuclear model improvements
- Transport code improvements - with improved nuclear models

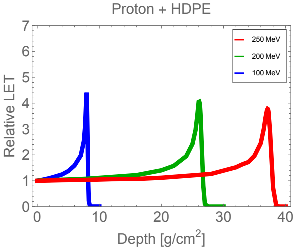
But biggest differences:

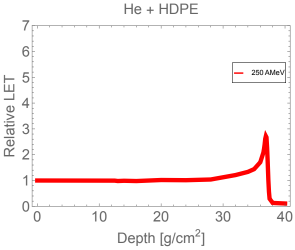
	Ion Therapy	Space Radiation
Energy	10s - 100s MeV/n	10s MeV/n – 50 GeV/n
Projectiles	H, He, C, O	H – Ni
Targets - human body	H, C, O, N, Ca, P, S, K, Na, Cl, Mg	H, C, O, N, Ca, P, S, K, Na, Cl, Mg
Targets - materials		C, Al, Cu, Ti

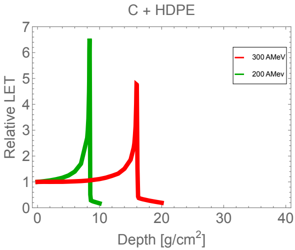
Thick & Thin

- Up to now, shielding relatively thin $\sim$ 20 g/cm^2 (except ISS, NAIRAS)
- International Space Station (ISS) shows considerable variation: 1 g/cm^2 – 4800 g/cm^2, median $\sim$ 54 g/cm^2 Thanks Dr. Tony Slaba
- Orion: 2 g/cm^2 – 820 g/cm^2, median $\sim$ 35 g/cm^2
- Earth atmosphere:
  1000 g/cm^2 (vertical) $\sim$ 50,000 g/cm^2 (horizontal)
  NAIRAS - Nowcast of Atmospheric Ionizing Radiation for Aviation Safety
- Mars atmosphere:
  20 g/cm^2 (vertical) $\sim$ 1000 g/cm^2 (horizontal)
- Future shields:
  - Moderate thickness - Lunar space station (Gateway); Commercial space stations
  - Very thick - Moon, Mars surface habitats; Mars transit vehicle
- Thick shields are real and represent future

THICK & THIN - EXAMPLE BRAGG CURVES

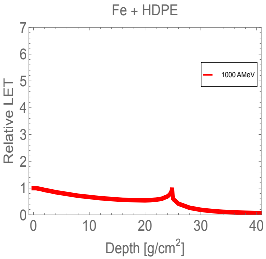


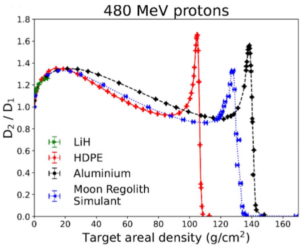


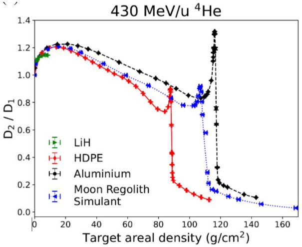


Generated from data at NASA Space Radiation Lab (NSRL)

HDPE = High Density PolyEthylene

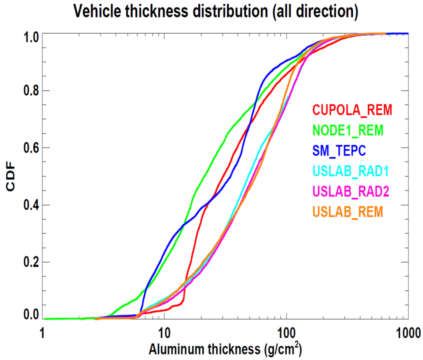


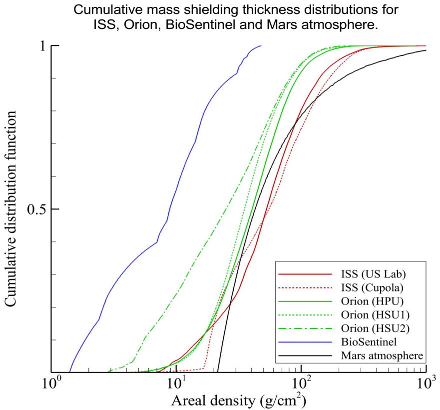




F. Luoni et al. Rad. Res. vol. 203, p. 163, 2025 [Open Access]

THICK & THIN - INTERNATIONAL SPACE STATION (ISS)

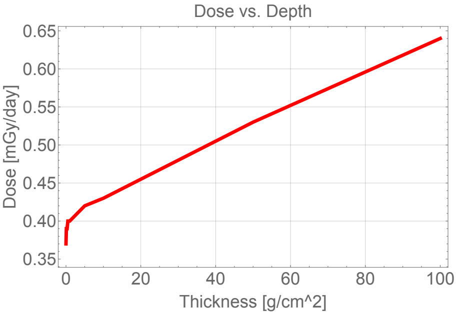


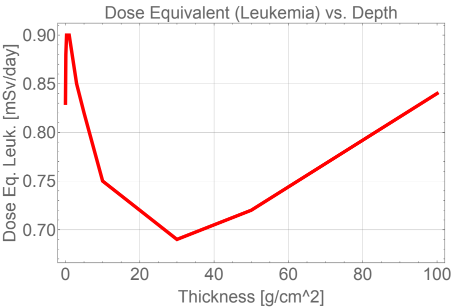


CDF = Cumulative Distribution Function

Slides courtesy of Dr. Tony Slaba - NASA

Thick & Thin





- Aluminum spherical geometry free space
- Dose increases $\rightarrow$ more particles being produced and depositing energy
- Dose Equivalent (H) - Famous minimum near 20 g/cm^2
  - H drops due to high LET particles breaking into lower LET
  - H starts increasing above 30 due to neutron buildup and elastic scattering protons
- Contrary to intuition, Dose Equivalent bigger at large depth (not smaller)
  - E.g. compare 20 g/cm^2 to 80 g/cm^2
  - Stay away from windows and stay away from thick walls
- Should eventually turn over ("Pfotzer")

Thick & Thin - Transport code disagreements

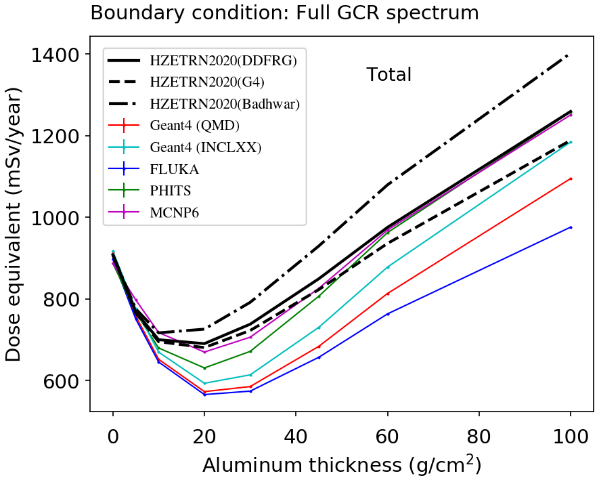


Figure courtesy of Dr. Tony Slaba - NASA

- Forward - Backward geometry
- Dose Equivalent - Famous minimum near 20 g/cm^2
- Code disagreements worse at LARGE DEPTH
- Large depth shielding highly uncertain
- Disagreement due to nuclear model differences
- Can't keep going up forever
- What happens $>$ 100 ?
- Beyond 100 g/cm^2 realistic thick shields

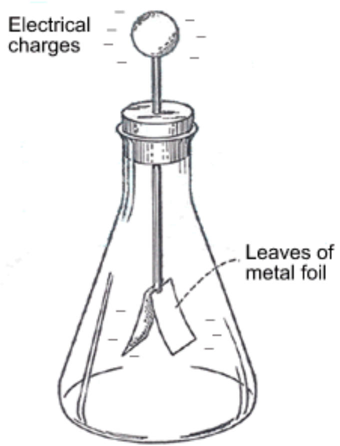
HZETRN (G4 - INCL nucleons only, not light, heavy ions etc.)
Thorough checks that all codes calculated quality factor same way
Similar disagreements seen for Dose and Flux

THICK & THIN - GCR - DISCOVERY

First thick target experiments by Coulomb, Wulf, Hess, Regener, Pfotzer

Beam = GCR, Target = Atmosphere, Detector = Electroscopes

- Began with a mystery concerning leakage of electric charge from an insulated charged electroscope.
- Unexplained since Henry Coulomb noticed in 1785, that charged metal sphere suspended by insulated silk thread did not retain charge.
- In early days electroscopes & electrometers also used to study x rays, radioactivity, etc.
- Strong sources of radiation cause leaves in electroscope to come together (after electroscope initially charged)
- Strength of radiation measured by how quickly leaves come together



[http://www.school-for-champions.com/experiments/]

THICK & THIN- GCR - DISCOVERY

Researchers found trouble:

- Turn off all Crookes tubes, remove all radiation sources, remove light
- Still electroscope leaves fall together

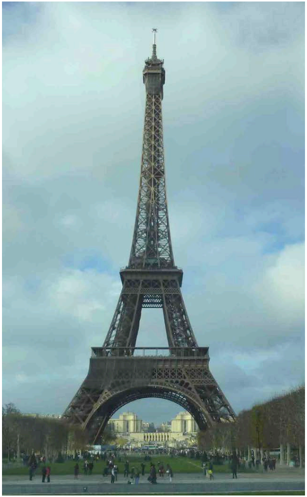
End C19 Wilson connected this to ionization of surrounding air

- With discovery of radioactivity & finding that earth itself contained minute traces of radioactive materials, it was mistakenly thought that source of ionization of air was this radioactive material of earth.

Implied that leakage rate (rate at which leaves come together) should be smaller at higher altitudes

1910 Father Thomas Wulf took electroscope top Eiffel tower

- Observed 64% drop in leakage rate
- But expected much more reduction (radiation should be absorbed in air)
- Deduced that radiation from ground (gradually decreasing with height) competing with radiation coming down through atmosphere
- Obvious thing was to go to greater heights (Wulf did not)



[Norbury, 2010]

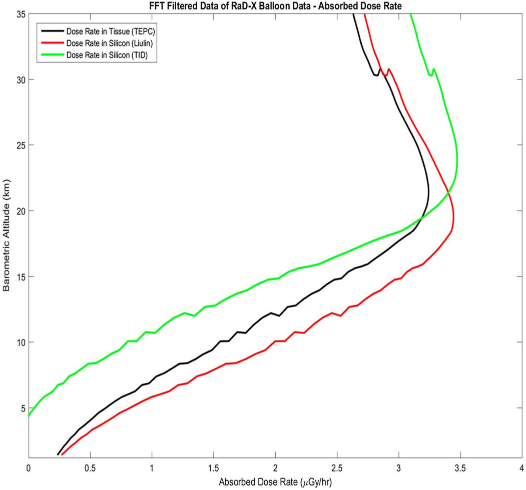
THICK SHIELDING - GCR - DISCOVERY

1911 - Victor Hess (Austrian)
- balloon flights with electroscopes

- Radiation first decreased as balloons went up
- But by 5,000 ft. radiation was more intense than at sea level
- By 17,500 ft. radiation increased several times
- Hess hypothesized “extra-terrestrial source of radiation”
- Nobel prize in physics
- Named *Cosmic Radiation* by Millikan in 1925

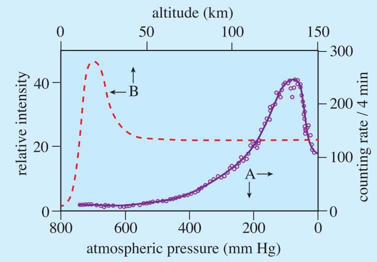
Friedlander, Nature 483, 400, 2012 [Public Domain]

Altitude (km) versus Dose Rate (μ Gy hour)



Mertens et al., Space Weather 15, 874, 2016

- 1930s Erich Regener - Georg Pfotzer balloon flights (Germany)
- 1935 discover Regener - Pfotzer max
- Height above Earth surface $\sim$ 20 km
- 2016 Mertens et al. (NASA) balloon flights, investigating in detail for airplane radiation (NAIRAS)



Bancroft et al., Phys. Ed. 49, 164, 2014
(reproduced with permission)

THICK & THIN - REGENER-PFOTZER MAXIMUM

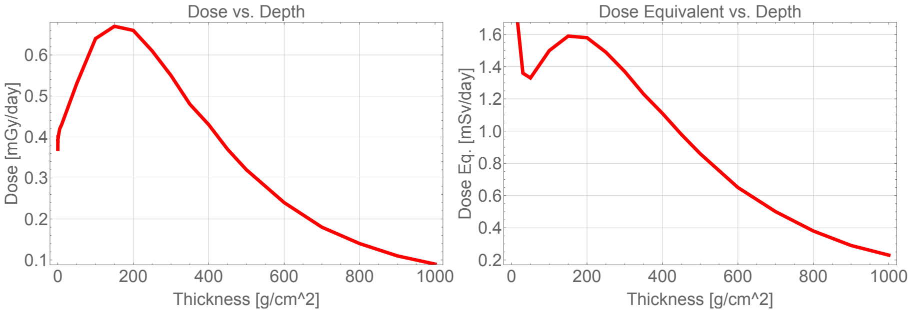
- Nowcast of Atmospheric Ionizing Radiation for Aviation Safety

NAIRAS, Mertens et al. (NASA)

- Domestic crews 1 - 2 mSv /yr
- International crews $<$ 4 mSv / yr
- Pregnant woman $<$ 5 mSv
  limit to fetus per pregnancy
- Many more polar flights
- Concorde & future commercial supersonic at Pfotzer max $\sim$ 30 km

Image courtesy of NASA

Aluminum sphere in free space at solar minimum



- Space radiation thick shield shows Pfotzer max near 200 g/cm^2
  - Both dose and dose equivalent

LIGHT IONS & NEUTRONS

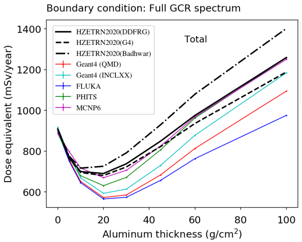


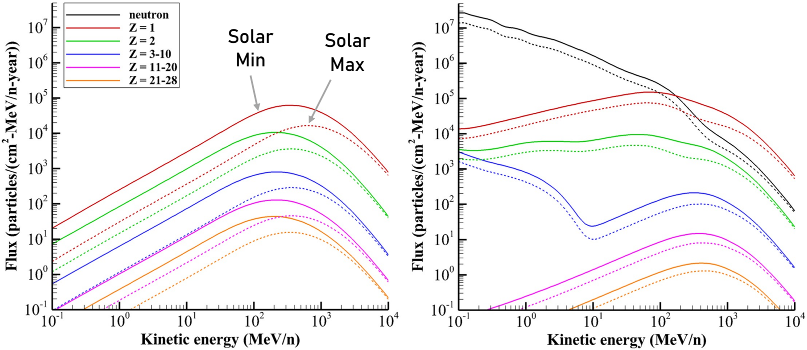
Figure courtesy Dr. Tony Slaba

- Want to understand cause of transport code disagreements
- What contributes most to dose versus depth curves?
  - Especially at large depth
- Explore Light Ions and Neutrons $\rightarrow$
  - Light ions are isotopes of Hydrogen & Helium
    proton = ^{1}H, deuteron = ^{2}H, triton = ^{3}H, helion = ^{3}He, alpha = ^{4}He

LIGHT IONS & NEUTRONS - GCR FLUX

Free Space

Female Blood Forming Organ Flux Behind 20 g/cm^2 Aluminum Shield



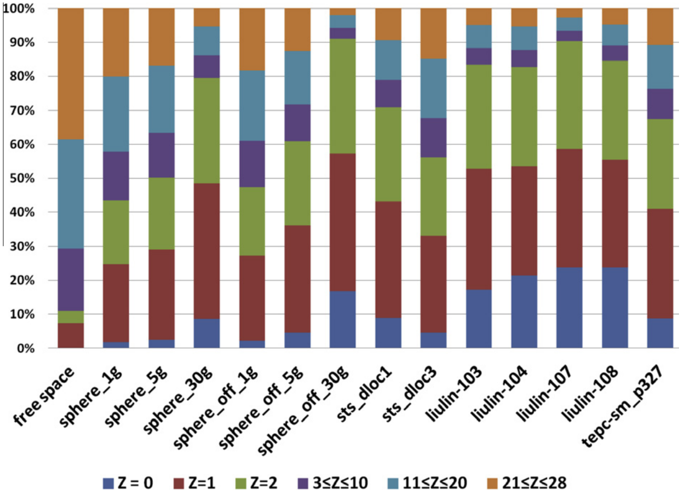
2010 Badhwar O'Neill GCR model
- **Solar Minimum: June 1976**
- **Solar Maximum: June 2001**

Image: Simonsen et al. (2020). *PLoS Biol* 18(5): e3000669. https://doi.org/10.1371/journal.pbio.3000669

Slide courtesy of Drs. Tony Slaba and Charlie Werneth - NASA

LIGHT IONS & NEUTRONS

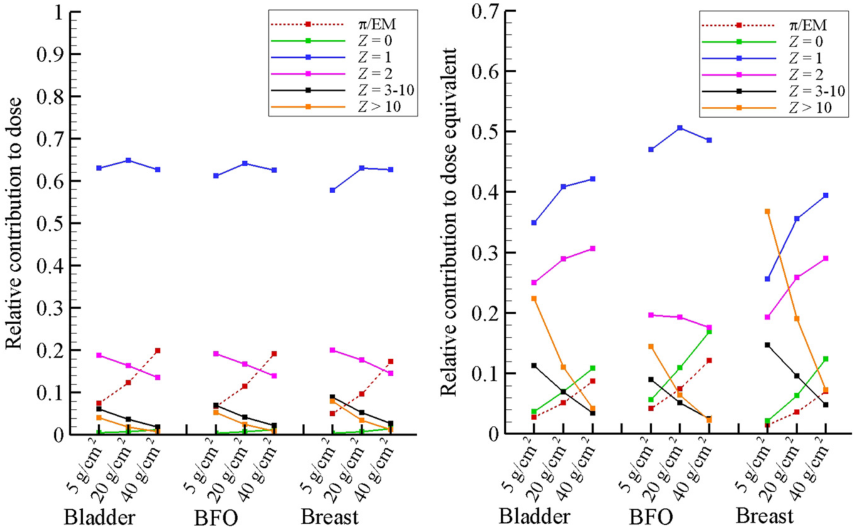
Percent contribution to blood forming organ (BFO) dose equivalent by charge group



Dose equivalent dominated by light ions & neutrons

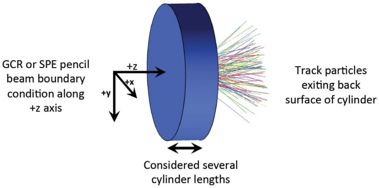
Walker, Townsend, Norbury, Adv. Space Res. 51, 1792, 2013

Percent contribution to organ dose equivalent by charge group



Slaba, Blattnig, Norbury, Rusek, La Tessa, Life Sci. Space Res. 8, 52, 2018

LIGHT IONS & NEUTRONS - TRANSPORT CODE COMPARISONS



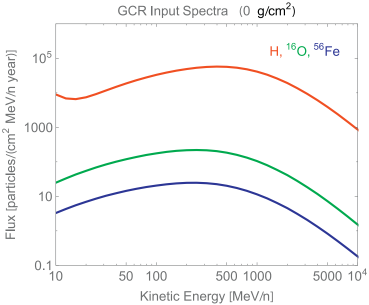
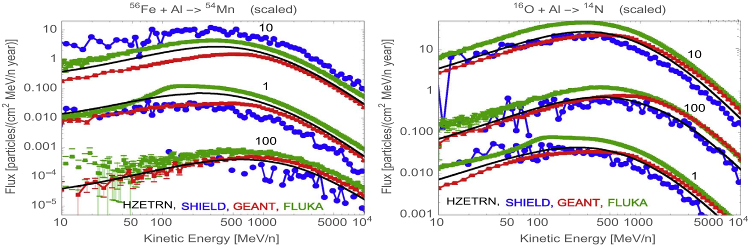


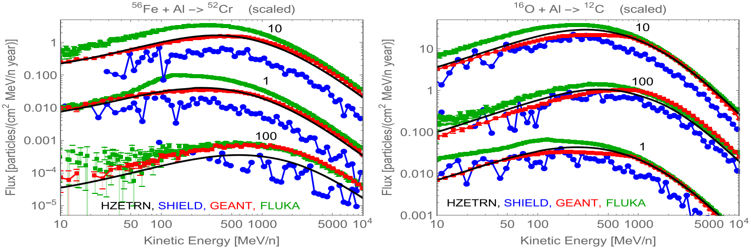
Fig. 2. GCR minimum spectra.

Norbury, Slaba, Sobolovsky, Reddell, Life Sci. Space Res. 14, 64, 2017

Flux spectra for varying shield depth 1, 10, 100 g/cm^2



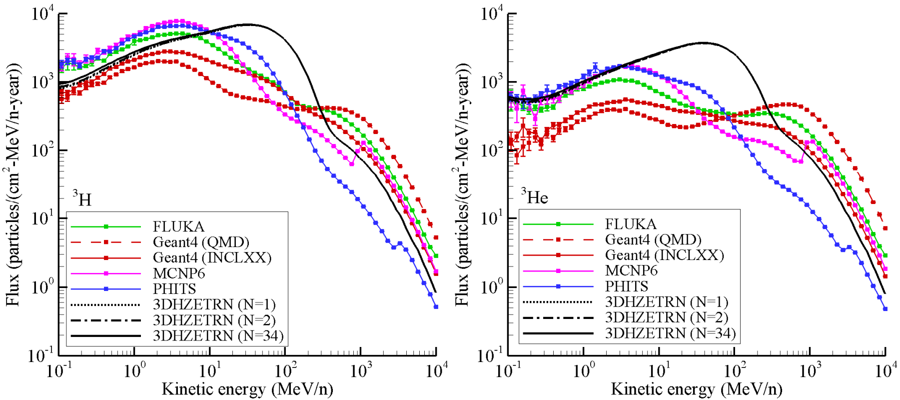
^{2}H, np *production discrepancies*



^{4}He, 2n2p *production discrepancies*

Norbury, Slaba, Sobolovsky, Reddell, Life Sci. Space Res. 14, 64, 2017

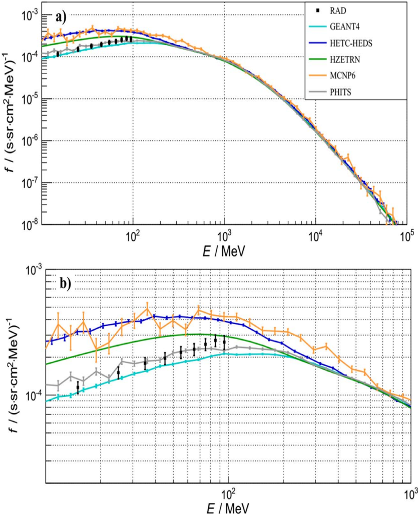
^{3}H and ^{3}He flux behind 60 g/cm^2 Al shield for GCR minimum spectrum - Thick targets



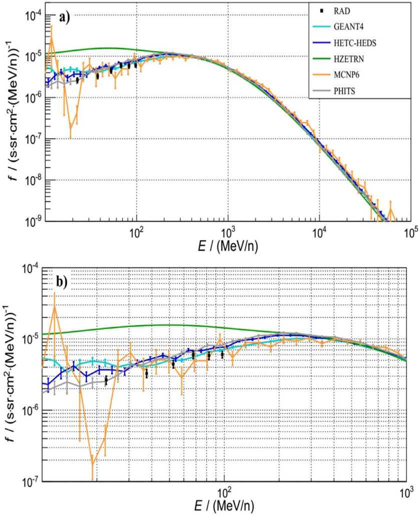
Slaba et al., Life Sci. Space Res. 12, 1, 2017

Significant discrepancies

Protons



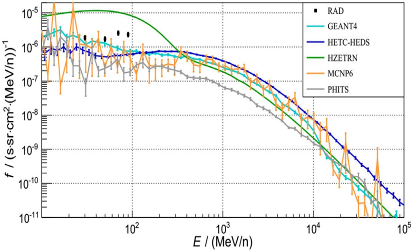
^{4}He



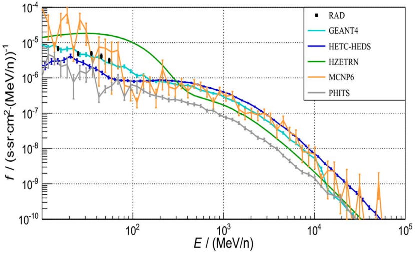
Low energy discrepancies

Matthia et al., Life Sci. Space Res. 14, 18, 2017

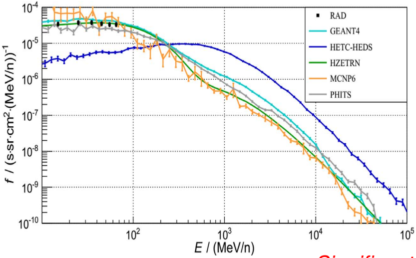
^{3}He



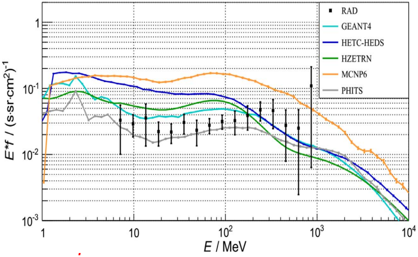
^{3}H



^{2}H



Neutrons



Significant discrepancies

Matthia et al., Life Sci. Space Res. 14, 18, 2017

Light ions & Neutrons - Discrepancies

- Light ions & neutrons dominate dose equivalent for realistic shield thicknesses ($\geq$ 20 g/cm^2) Norbury & Slaba, Life Sci. Space Res. 3, 90, 2014
- Light ions & neutrons are scattered at large angles
  - Require 3-dimensional transport & nuclear physics
  - 3DHZETRN & double differential cross sections
- Transport codes show largest differences for light ions
  - GEANT, FLUKA, MCNP, PHITS, HZETRN, SHIELD
  - Due to uncertain light ion nuclear physics models (coalescence & heavy ion breakup) and lack of experimental data
- Thick target measurements show significant discrepancies compared to transport codes (MCNP, PHITS) for light ions
- MSLRAD light ion flux measurements highlight need for improved nuclear interaction models
  - Light ion model results show significant discrepancies over MSLRAD energy range
  - Model errors due to inaccurate light ion nuclear physics models
  - Discrepancies don't contribute significantly to dose equivalent, but improvements would yield better agreement with MSLRAD

- Light ion cross sections
  - Largest physics uncertainty in space radiation
- Light ion cross section measurements
  - Largest gap in cross section database

  Norbury et al., Rad. Meas. 47, 315, 2012
- Light ion cross section measurements needed
  - To improve inaccurate light ion nuclear physics models

GALACTIC COSMIC RAYS (GCR)

- Protons $\rightarrow$ Fe nuclei $\sim$ 100 MeV/n – 50 GeV/n
- Peaks: H, He, C, O, Si, Fe   Z = 1, 2, 6, 8, 14, 26

NUCDAT (50,000 entries):

Norbury et al.,

Radiation Measurements 47, 315, 2012

Health Physics 103, 640, 2013

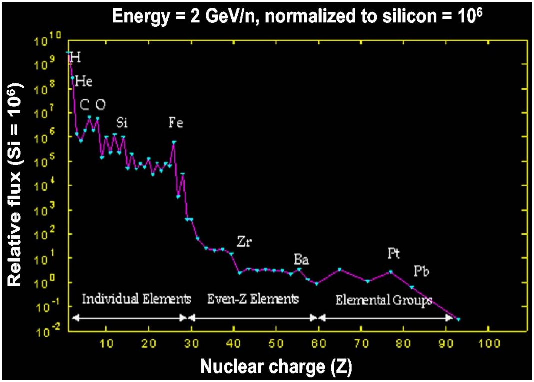
Journal of Physics (conf. ser.) 381, 012117, 2013

Frontiers in Physics 8:565954, 2020

GSI Nuclear database:

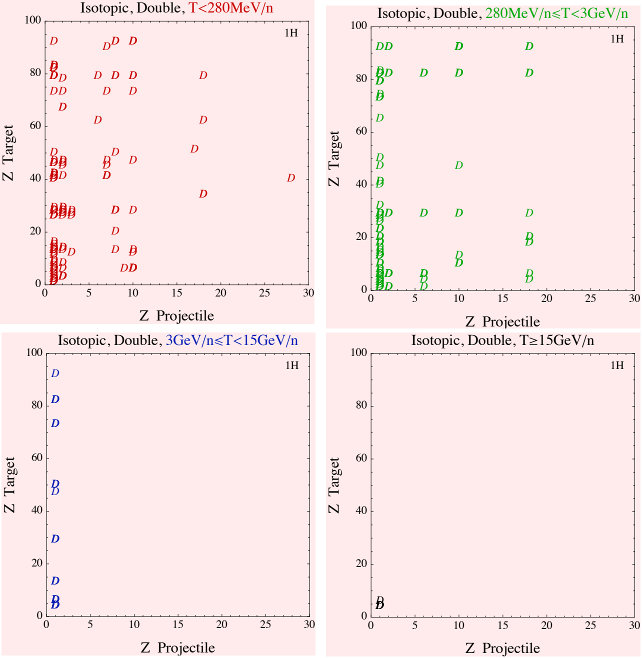
Luoni et al., New Journal Physics 23, 101201, 2021

https://bioapp.gsi.de/cross-section-db/



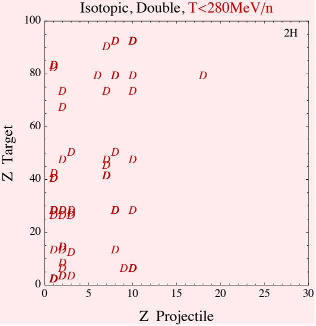
Cross section measurement database

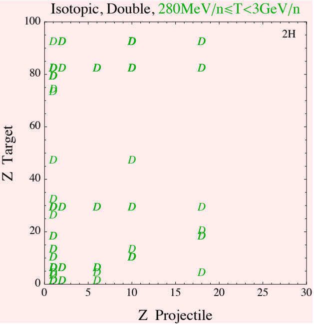
- NUCDAT database: $\sim$ 50,000 entries
  - ZP, AP, TP, ZT, AT, ZF, AF
  - Cross section type
    - total, differential, charge changing, elemental, isotopic, ...
  - Double differential most useful
  - Bibliography
  - Other
  - No actual data - only that data exists
- Energy regions:
  - Below pion threshold: $\mathrm{T} < 280\,\mathrm{MeV/n}$
  - Low: 280 MeV/n $\leq$ T $<$ 3 GeV/n
  - Medium: $3\,\mathrm{GeV/n} \leq \mathrm{T} < 15\,\mathrm{GeV/n}$
  - High: $\mathrm{T} \geq 15\,\mathrm{GeV/n}$
- Fragments:
  - Light (H, He) - TODAY ONLY
  - Medium-Light $(\mathrm{Z_F} = 3 - 9)$ $(\mathrm{Li} - \mathrm{F})$
  - Medium $(\mathrm{Z_F} = 10 - 19)$ $(\mathrm{Ne} - \mathrm{K})$
  - Heavy $(\mathrm{Z_F} = 20 - 30)$ $(\mathrm{Ca} - \mathrm{Zn})$
  - Very Heavy $(\mathrm{Z_F} > 30)$



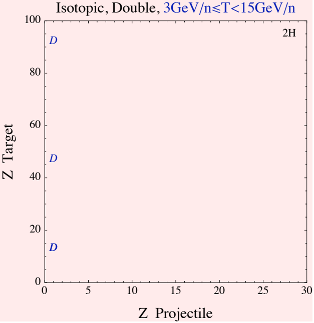
$$^{1}\mathrm{H} \quad \frac{d^2\sigma}{dE\,d\Omega}$$

GCR peaks Z = 1, 2, 6, 8, 14, 26

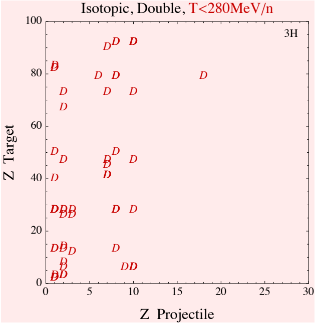


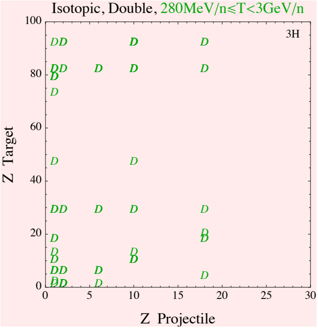


$$^{2}\mathrm{H}\ \frac{d^2\sigma}{dE\,d\Omega}$$

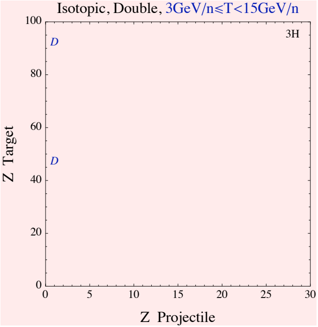


GCR peaks Z = 1, 2, 6, 8, 14, 26

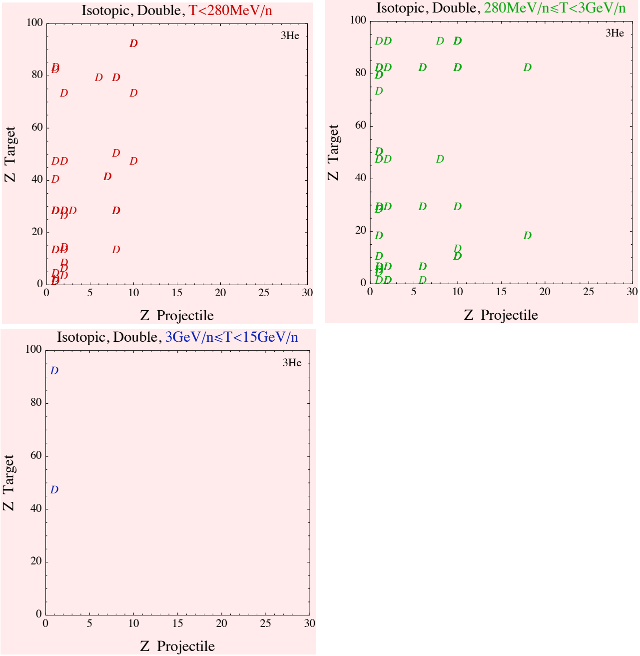




$^{3}\mathrm{H}\ \frac{d^2\sigma}{dEd\Omega}$

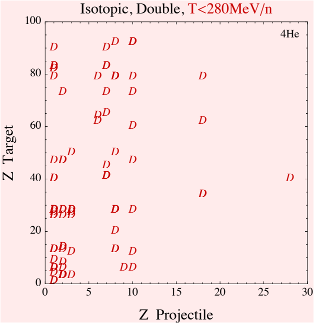


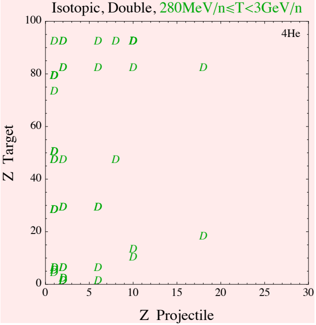
GCR peaks Z = 1, 2, 6, 8, 14, 26



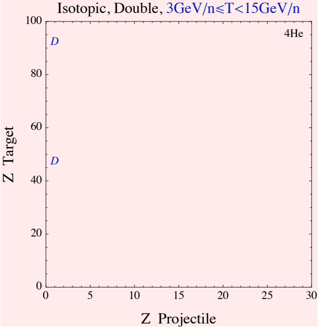
$^{3}\text{He}\ \frac{d^2\sigma}{dE\,d\Omega}$

GCR peaks Z = 1, 2, 6, 8, 14, 26





$^{4}\mathrm{He}\ \frac{d^2\sigma}{dE d\Omega}$



GCR peaks Z = 1, 2, 6, 8, 14, 26

Additional double-differential measurements:

- M. Beach, L. Heilbronn et al. (unpublished)
  NASA Space Radiation Lab at Brookhaven National Lab
  ^{16}O (300 MeV/n), ^{56}Fe (600 MeV/n) + Al, C, CH_4 $\rightarrow$ ^{1,2,3}H, ^{3,4}He
  - data tables

- Toppi et al. (FIRST-GSI), Phys. Rev. C vol. 93, p. 064601, 2016
  ^{12}C (400 MeV/n) + Au $\rightarrow$ ^{1,2,3}H, ^{3,4}He, ^{6,7}Li, ^{7,9,10}Be, ^{10,11}B
  - data tables published

- Mattei et al., IEEE Transactions on Radiation and Plasma Medical Sciences, 4, 269, 2020
  ^{12}C (115 - 353 MeV/n) + H, C, O $\rightarrow$ ^{1,2,3}H
  - data tables published

FINAL RECOMMENDED REACTIONS

Fe,Si,O,He + H,C,Al,Cu $\rightarrow$ ^{1,2,3}H, ^{3,4}He (isotopic dd & total reaction σ)

3 GeV/n, 1.5 GeV/n, 800 MeV/n, 400 MeV/n

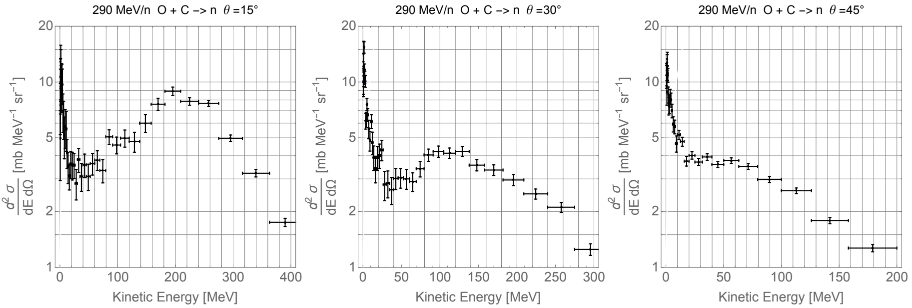
dd = double differential

- Projectile priorities: 1) Fe 2) Si 3) O 4) He
- Targets: H, C, Al (all equal priority), Fe (lesser priority)
  – CH_2 target easier than H target - get H σ from CH_2 target by subtracting C σ
- Energy priorities: Span range of energies available above 300 MeV/n, with more emphasis on higher energies
  3 GeV/n, 1.5 GeV/n, 800 MeV/n, 400 MeV/n
  – based on contribution to effective dose & lack of high energy data
  – need all energies to properly test models
  – Fe gap greater at higher energy.

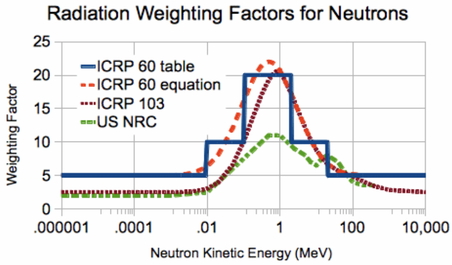
NEUTRONS

- Major neutron reference:
  - Nakamura & Heilbronn, *Handbook on secondary particle production and transport by high-energy heavy ions* (World Scientific, Singapore, 2006)
  - BEVALAC (337 MeV/n)
  - HIMAC (230 - 600 MeV/n)
  - RIKEN (95, 135 MeV/n)

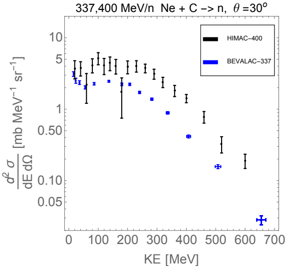
Neutrons - Low energy neutron peak

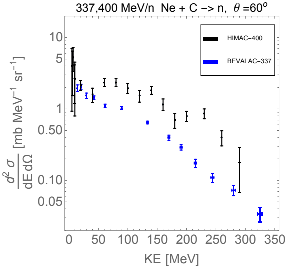


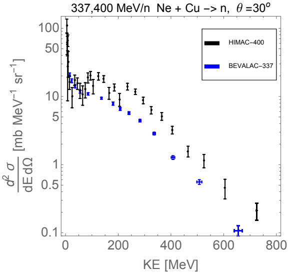
- Low energy neutron peak near 1 MeV
  - only measured in a few experiments
  - No Coulomb barrier
- Not present in proton data
  - Coulomb barrier present

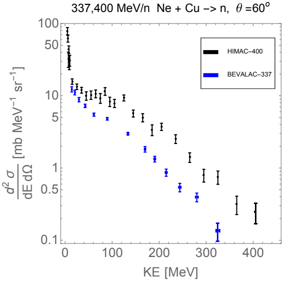


[Wikimedia commons]



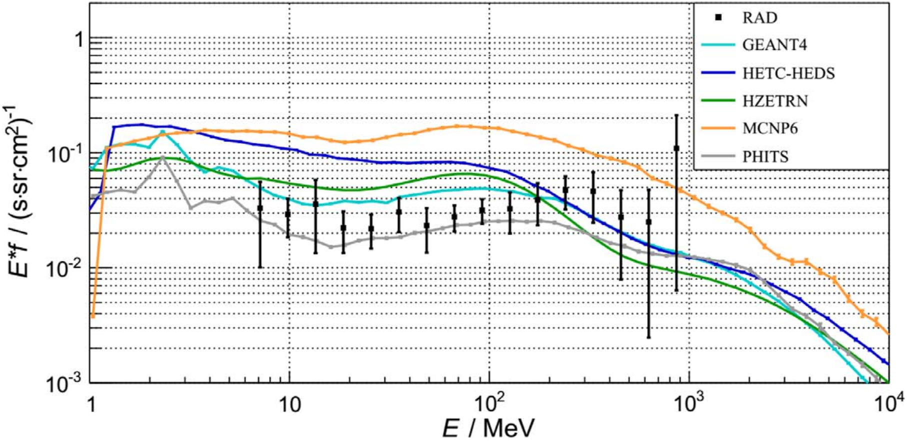






BEVALAC and HIMAC data disagree

NEUTRONS - MSLRAD COMPARISONS



Matthia et al., Life Sci. Space Res. 14, 18, 2017

Significant discrepancies

NEUTRONS - SUMMARY

- BEVALAC and HIMAC data disagree

- Neutron spectra display prominent low energy peak not seen in proton spectra

  - but only a few experiments down to 1 MeV

- No data above 1 GeV/n projectile kinetic energy

SUMMARY & CONCLUSIONS

- Light ions & neutrons make large contributions to dose equivalent
- Light ion cross sections
  - Largest physics uncertainty in space radiation
  - Large gap in measurement database
- Final recommended reactions
  - Fe,Si,O,He + H,C,Al,Cu $\rightarrow$ ^{1,2,3}H, ^{3,4}He
  - Isotopic dd & total reaction σ
  - 3 GeV/n, 1.5 GeV/n, 800 MeV/n, 400 MeV/n
- Neutrons
  - BEVALAC/HIMAC data disagreement needs resolution
  - Nothing above 1 GeV/n
- Data disagreement: Should other data be confirmed? Yes.
- Future Suggestions
  - Databases & tables in papers
  - Nuclear models collaboration
  - Transport codes collaboration
  - Uncertainty Quantification (UQ)

Acknowledgements:

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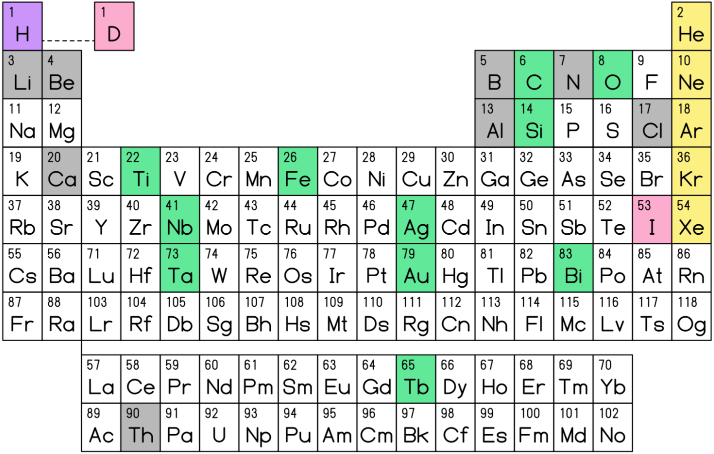
Thanks also Drs. Chris Mertens, Martha Clowdsley, Steve Blattnig,
Chris Sandridge, Robert Singleterry, Francesca Luoni

john.w.norbury@nasa.gov

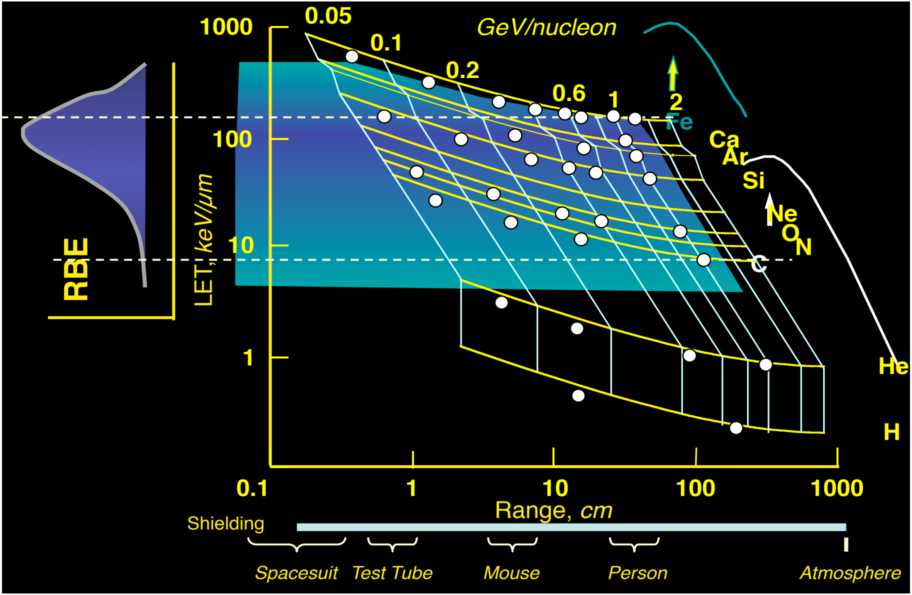
THE END



- Readily available
- Protons, very likely available but requires notice
- Noble gas, limited availability
- Requires Tandem Van de Graaff ion source
- Delivered to NSRL in the past

Ion Species	Maximum Energy [MeV/u]	LET in Si at Maximum Energy [MeV-cm²/mg]	Peak LET in Si [MeV-cm²/mg]	Range in Si [mm]
^{1}H	2500	0.001665	0.48	5580
D (^{2}H)	1125	0.001764	0.48	4079
^{4}He	1500	0.006799	1.5	2963
^{12}C	1500	0.0593	5.1	1020
^{16}O	1500	0.1074	7.2	749
^{20}Ne	1000	0.177	9.0	351
^{28}Si	1000	0.351	14.0	247
^{40}Ar	1000	0.600	18.7	207
^{48}Ti	1000	0.854	24.3	175
^{56}Fe	1000	1.189	29.4	146
^{84}Kr	383 *(721)*	3.26 *(2.54)*	41.0	26.9 *(70.4)*
^{93}Nb	520	3.64	47.5	37.5
^{107}Ag	575	4.66	59.4	37.9
^{127}I	448	6.55	68.9	24.2
^{129}Xe	350 *(589)*	7.67 *(6.16)*	69.3	16.1 *(35.8)*
^{159}Tb	446	9.32	78.2	21.4
^{181}Ta	390 *(475)*	12.7 *(11.7)*	87.7	15.6 *(21.1)*
^{197}Au	242 *(425)*	19.2 *(14.7)*	94.4	6.9 *(16.4)*
^{209}Bi	385	17.0	100.0	13.5

BACKUP: LET VS. RANGE, ENERGY



Details of light ion production double differential cross sections:

Proj.	KE MeV/n	Target	Fragment	Author	Note	Comments
^{1}H	100 - 200	Ni,Mo,Au	^{1}H	Richter 1982	0^{o} - 140^{o}	
^{1}H	500	^{4}He,Ni,Ta	^{1}H	Roy 1981	> 65^{o}	
^{1}H	600	C, Al, Au,	^{1,2,3}H, ^{3,4}He	Alard 1975	> 30^{o}	
^{1}H	660	B,Ni,Sn,Sm	^{3,4}He	Bogatin 1976	90^{o}	
^{1}H	800	^{1,2}H,C,Ca,Pb	^{1}H	McGill 1984	> 5^{o}	
^{1}H	800	KCl	^{1}H	Nagamiya 1981	> 10^{o}	
^{1}H	1050, 2100	Au	^{1}H	Geaga 1980	2.5^{o}, 180^{o}	
^{2}H	1050	C	^{1}H	Anderson 1983	0^{o}	Fig.7
^{2}H	2100	U	^{4}He	Gossett 1977	90^{o}	Fig.6* (* only lines)

Cross section measurement database - Details

Proj.	KE MeV/n	Target	Fragment	Author	Note	Comments
^{3}He	33 (exception)	Ho	^{1,2,3}H	Motobayashi 1984		
^{3}He	67 (exception)	Ag	^{1}H	Zhu 1991	> 33^o	
^{4}He	27 (exception)	Ho	^{1}H	Shibata 1985	15^o - 150^o	
^{4}He	180	Al, Ag, Ta	^{1,2,3}H, ^{3,4}He	Doering 1978	> 60^o	
^{4}He	383	C	^{1,2,3}H, ^{3}He	Anderson LBL-6769	0^o	Fig.24
^{4}He	250	U	^{1,2,3}H, ^{3,4}He	Gossett 1977	> 20^o	Fig.10*
^{4}He	400	U	^{1}H	Westfall 1976	> 30^o	Fig.3
^{4}He	400	U	^{1,2,3}H, ^{3,4}He	Gossett 1977	> 20^o	Fig.10*
^{4}He	400	U	^{1}H, Li, ^{7,9,10}Be, B	Gossett 1977	> 30^o	Fig.18*,26
^{4}He	400	C	^{1}H	Anderson 1983	0^o	Fig.23 xF
^{4}He	1010	H	^{3}He	Bizard 1977	1 - 10^o	
^{4}He	1050	^{2}H, ^{3,4}He	^{4}He	Banaigs 1987	< 15^o	Elastic & inelastic
^{4}He	1050	C	^{1}H	Anderson 1983	0^o	Fig.7
^{4}He	1050	C	^{4}He	Anderson 1983	pT	Fig.10
^{4}He	1050	C	^{1,2,3}H, ^{3}He	Anderson 1983	0^o	Fig.3
^{4}He	1050, 2100	C	^{1}H	Anderson 1983	0^o	Fig.23 xF
^{4}He	1050, 2100	C	^{1,2,3}H, ^{3}He	Anderson LBL-6769	0^o	Fig.25,26
^{4}He	1050, 2100	C	^{1}H	Anderson 1983	0^o	Fig.21
^{4}He	2100	C	^{1}H	Anderson 1983	pT	Fig.8
^{4}He	2100	H, C, Cu, Pb	^{4}He	Anderson 1983	pT	Fig.10
^{4}He	2100	C	^{1}H	Anderson LBL-6769	pT	Fig.28
^{4}He	2100	U	^{4}He	Gossett 1977	90^o	Fig.6*

Cross section measurement database - Details

Proj.	KE MeV/n	Target	Fragment	Author	Note	Comments
^{12}C	35 (exception)	Au	^{1,2,3}H, ^{3,4,6}He	Westfall 1984	> 40^o	
^{12}C	800	C, KCl	^{1,2,3}H, ^{3,4}He	Nagamiya 1981	> 10^o	Lemaire supplement
^{12}C	1050	C	^{1,2,3}H, ^{3,4,6,8}He	Anderson 1983	< 10^o	Fig.4,7,10
^{12}C	1050, 2100	Au	^{1}H	Geaga 1980	2.5^o, 180^o	
^{12}C	2100	U	^{4}He	Gossett 1977	90^o	Fig.6*
^{16}O	52, 100, 147	Ni, Sn	^{1,2,3}H, ^{3,4}He	Auble 1983	> 6^o	
^{16}O	300	Al	^{1,2,3}H, ^{3,4}He	Beach 2016	0^o - 90^o	Analysis in progress
^{16}O	2100	U	^{4}He	Gossett 1977	90^o	Fig.6*
^{20}Ne	100, 156		^{1,2}H, ^{4}He	Westfall 1982	> 50^o	
^{20}Ne	250, 400	U	^{1,2,3}H, ^{3,4}He	Gutbrod 1976	30^o - 150^o	Same as Gosset ???
^{20}Ne	250, 400, 2100	U	^{1}H	Westfall 1976	> 30^o	Fig.3
^{20}Ne	250, 400, 2100	U	^{1,2,3}H^{3,4}HeLi^{7,9,10}BeBCNO	Gossett 1977	> 20^o	
^{20}Ne	250, 400, 2100	Al	^{1,2,3}H, ^{3,4}He	Gossett 1977	> 20^o	Fig.7*,8*,9*,11*,26,29
^{20}Ne	400, 2100	U	^{1,2,3}H, ^{3,4}He	Gossett 1978	> 30^o	Fig.1,2,3,4,5
^{20}Ne	800	NaF, Pb	^{1}H	Gossett 1978		Fig.9,11 Rapidity
^{20}Ne	2100	U	^{4}He	Gossett 1977	90^o	Fig.6*
^{20}Ne	2100	U	^{3,4,6}He, ^{6,7,8}Li, ^{7,9,10}Be	Gossett 1977	90^o	Fig.5
^{40}Ar	1050, 2100	Au	^{1}H	Geaga 1980	2.5^o, 180^o	
^{40}Ar	800	C, KCl	^{1,2,3}H, ^{3,4}He	Nagamiya 1981	> 10^o	Lemaire supplement
^{40}Ar	1800	Be, Cu	^{1,2,3}H	Gossett 1978	5^o, 15^o	Fig.6,7,8
^{40}Ar	1800	Be, Cu	^{1,2,3}H	Gazzaly 1978	5^o - 15^o	
^{56}Fe	400	CH_2, C, Al	^{1,2,3}H, ^{3,4}He	Beach 2017	0^o - 90^o	Analysis in progress