Review and Development of Nuclear-Nuclear Interaction Physics Models for Geant4

Contract 17191/03/NL/LvH

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Outline

- Project overview
- Background and requirements
- Geant4
- Physics models implemented
- Results and comparison with experiment and other models
- Summary

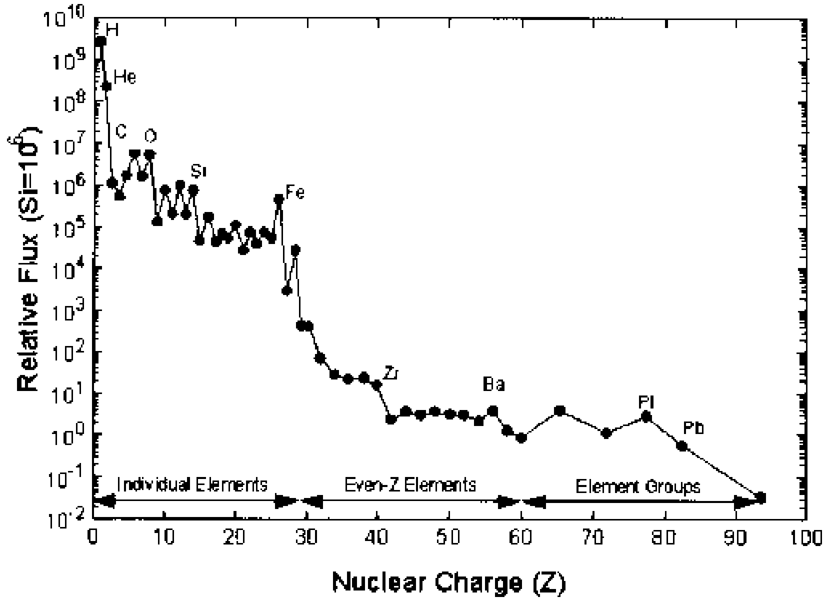
Project Overview

Ion-Nuclear Models for Analysis of Radiation Shielding and Effects

- WP 1 Review
  - Review requirements, models and available data
  - Summarise in Technical Note #1 & URD
- WP2 Implementation
  - SSD, SUM
- WP3 Validation
  - SVVP, Technical Note #2
- WP4 Software maintenance
  - Maintained for 2 year period
  - Modifications timed to coincide with major Geant4 releases during this period

Background and Requirements

- Species and energy range of source particles
  - GCR:
    - Very wide range in species, with noticeable dips after He and Fe
    - Typical energy range of concern: 10's MeV/A - 100's GeV/A, although mean energy is several hundred MeV/A.



  - Solar particle events 10's MeV/A to ~1 GeV/A:
    - Impulsive, short-term events associated with solar flares have greater fraction of heavy particles
    - CMEs produce gradual events that are proton-rich and last longer

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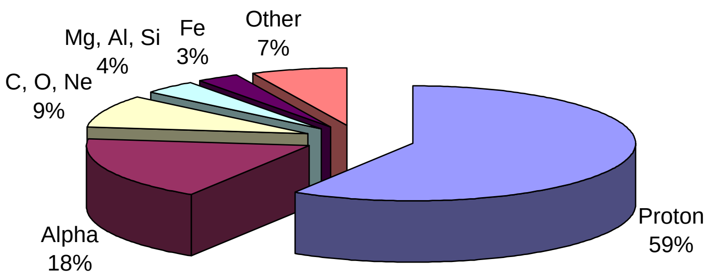
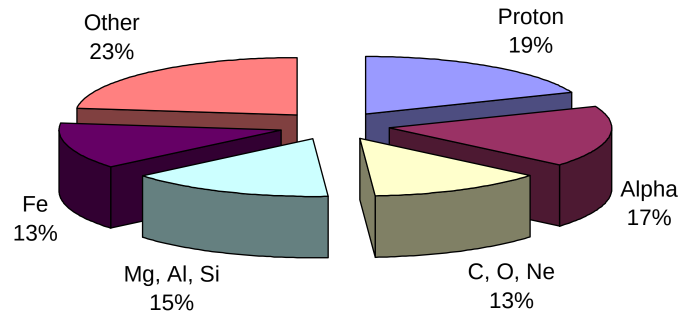
Background and Requirements

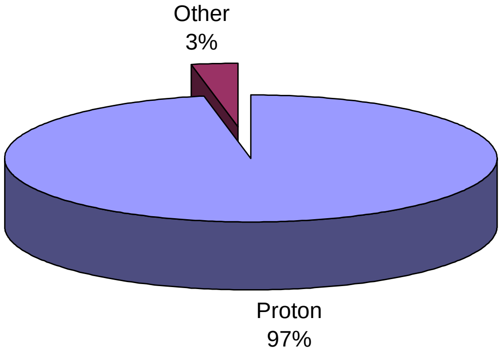
Dose - GCR



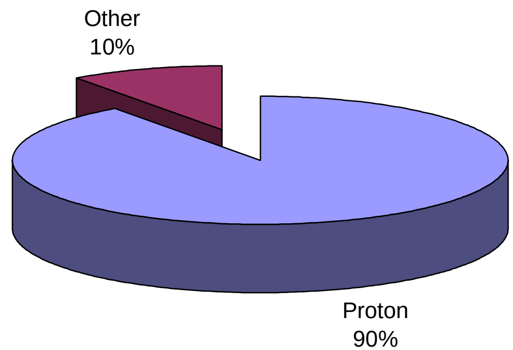
Dose Equivalent - GCR



Dose - SPE



Dose Equivalent - SPE



Data from W Schimmerling, J W Wilson, F Cucinota, and M-H Y Kim, 1998.

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Target materials involved

- Man-made / transported materials
  - Metal alloys of Al, Ti, Fe, Mg, Be
  - plastics and composites (incl glass, B and C-fibre)
  - oxidants and fuels (*e.g.* UDMH + NO_x)
  - deliberate shielding and mass balance (polyethene, water, W, Ta, Cu, Fe)
  - fissionable materials (namely uranium isotopes) if nuclear-powered propulsion used
  - crew consumables / life support

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Martian and Lunar Soils

- Soil model based on previous NASA Langley studies:

	Lunar Langley model	Mars Rep. Regolith	Mars Basalt
– O	61.5%	40.4%	61.3%
– Si	19.3%	14.1%	19.2%
– Al	7.5%		3.3%
– Fe	6.1%	4.4%	6.1%
– Mg	5.5%	39.2%	6.2%
– Ca		1.9%	4.1%

Work on extending QGS to treat nuclear-nuclear

Very detailed model ∴ time consuming

Regime		...plication
Hadron-nucleon or hadron-nuclear	Parameterised	
	Parton-string (>5GeV)	Cosmic ray nuclei and secondaries
	Cascade (10MeV-10GeV)	
	QMD models	Trapped protons and secondaries
	Pre-compound (2-100 MeV)	
	Low-energy neutron (thermal - 20 M...	...g ... neutrons
	Isotop...	...d
	Evapor...	...ment for seondaries from cosmic ray nuclei and trapped protons, esp. important in calculation of single event effects (microdosimetry)
	Fermi br... ...)	
	Fission (A≥65)	
	Multi-fragmentation	
	Photo-evaporation (ENSDF)	Induced and natural radioactive backgrounds
	Radioactive decay (ENSDF)	

At the time could only treat hadron-nuclear interactions (Light-ion Binary Cascade code released Dec 03)

Any new models have to complement and not duplicate other hadronics development in the Geant4 Collaboration.

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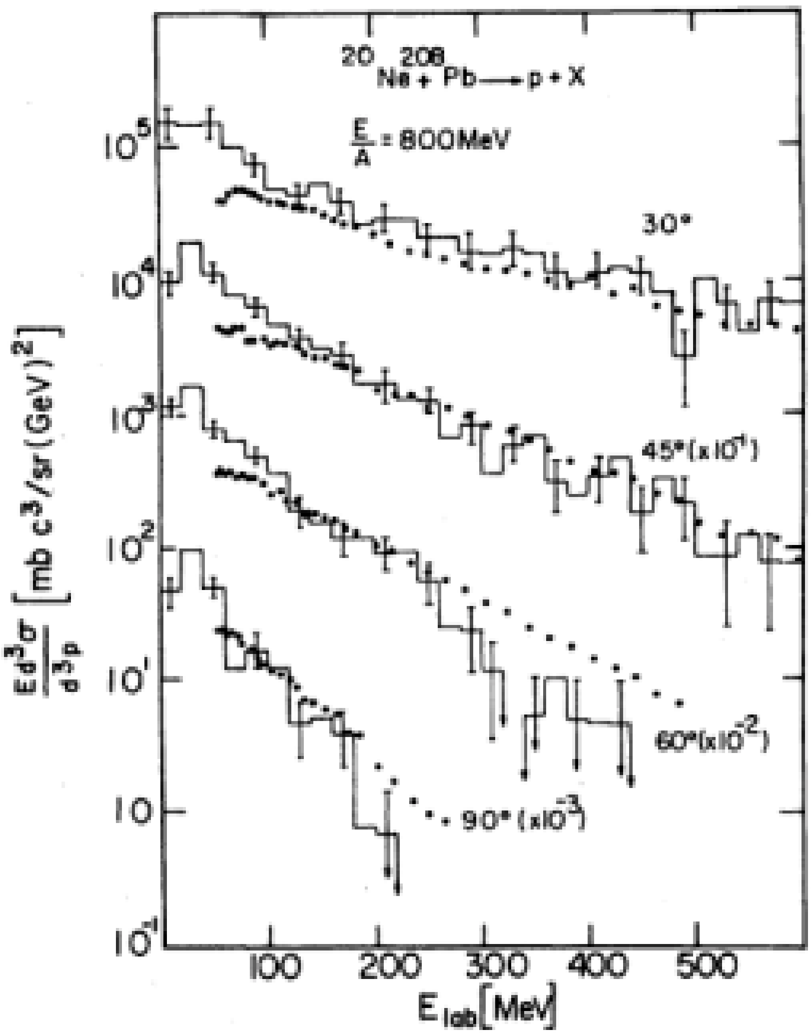
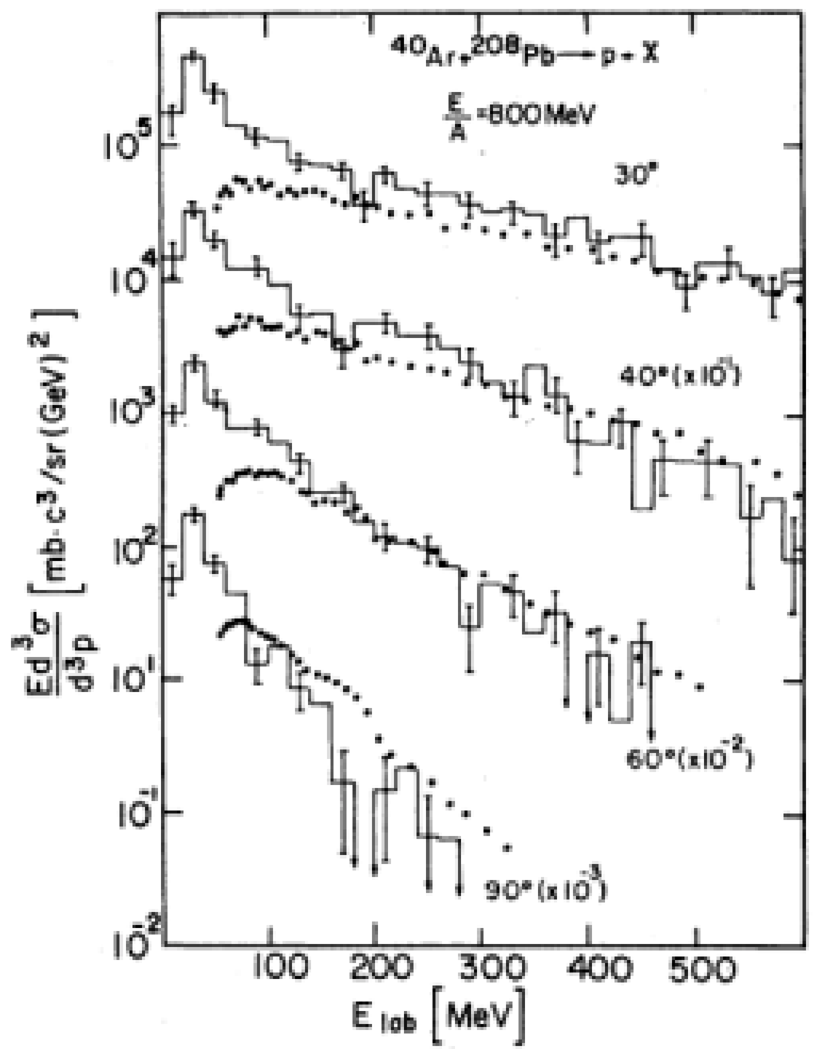


$^{20}Ne + ^{208}Pb \longrightarrow p + X$
$\frac{E}{A}$ = 800MeV
30°
45° (x10^{-1})
60° (x10^{-2})
90° (x10^{-3})
$\frac{Ed^3\sigma}{d^3p}$ [mb c^3/sr (GeV)^2]
E lab [MeV]



$^{40}Ar + ^{208}Pb \longrightarrow p + X$
$\frac{E}{A}$ = 800MeV
30°
40° (x10^{-1})
60° (x10^{-2})
90° (x10^{-3})
$\frac{Ed^3\sigma}{d^3p}$ [mb·c^3/sr (GeV)^2]
E lab [MeV]

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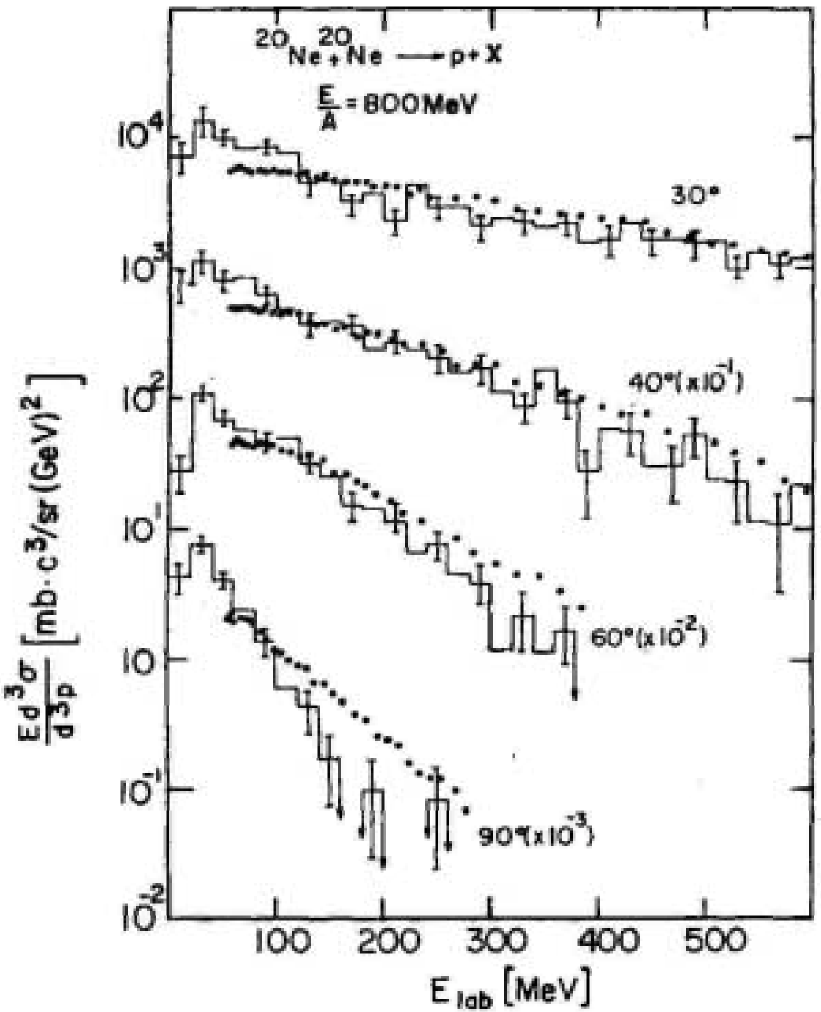
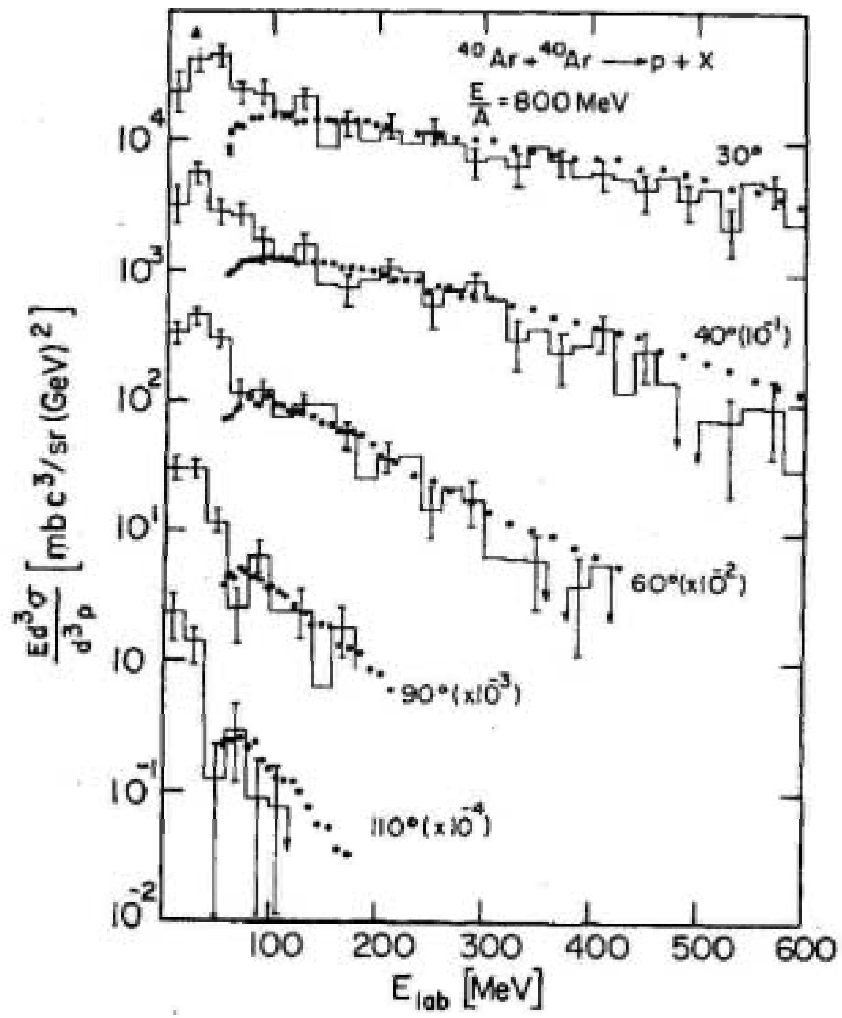


$^{20}Ne + ^{20}Ne \longrightarrow p + X$
$\frac{E}{A}$ = 800 MeV
30°
40°(x10^{-1})
60°(x10^{-2})
90°(x10^{-3})
$\frac{E d^3\sigma}{d^3p}$ [mb·c^3/sr (GeV)^2]
E lab [MeV]



$^{40}Ar + ^{40}Ar \longrightarrow p + X$
$\frac{E}{A}$ = 800 MeV
30°
40°(10^{-1})
60°(x10^{-2})
90°(x10^{-3})
110°(x10^{-4})
$\frac{E d^3\sigma}{d^3p}$ [mb c^3/sr (GeV)^2]
E lab [MeV]

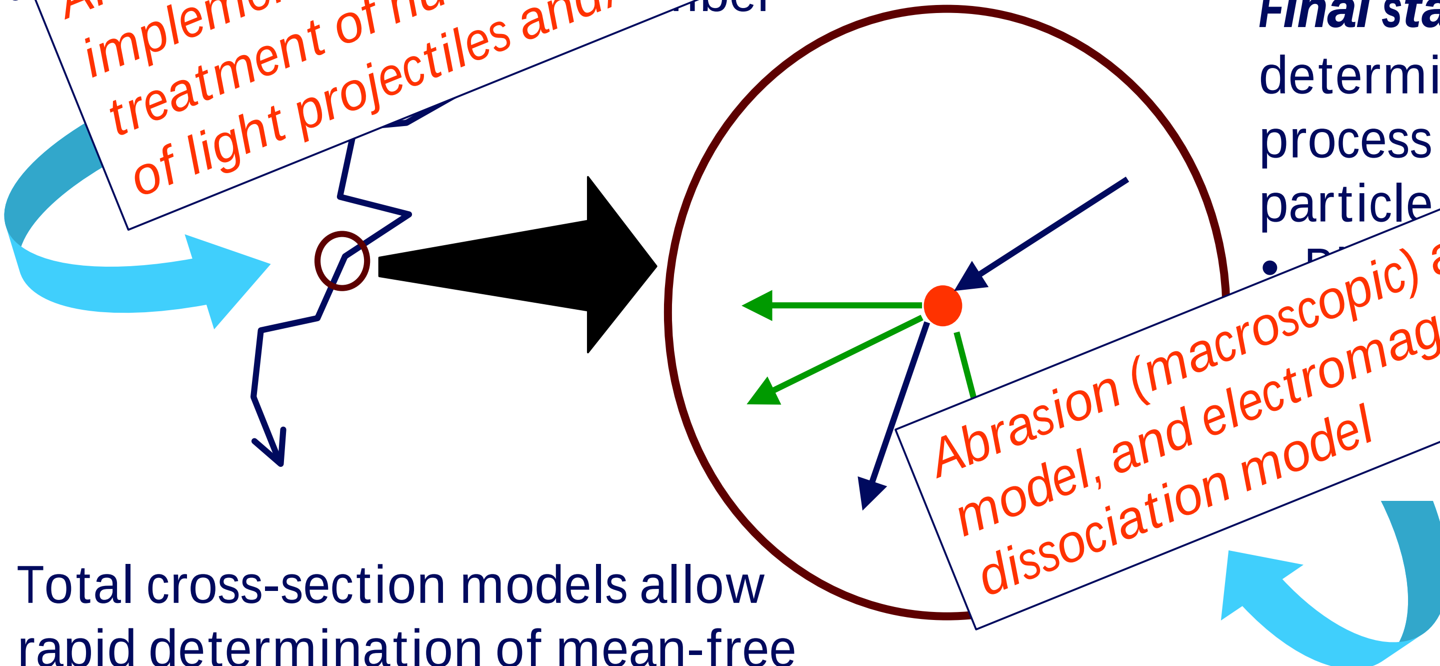
Geant4 Inelastic C… s-Sections

Total cross-section m… …metric fits:
- proton-nu… …actions
- Trip… …or nuclear-nuclear
- … …ber

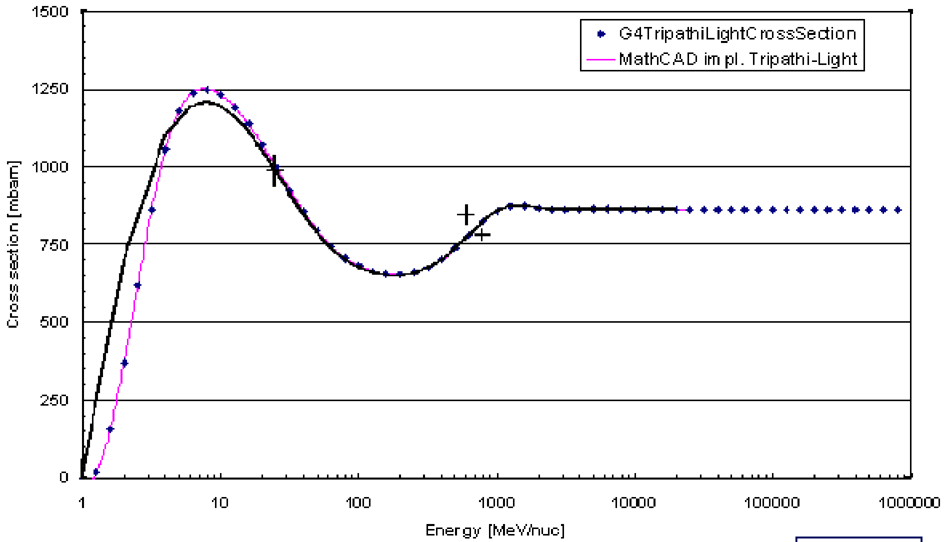
Alternative model of Tripathi implemented for more accurate treatment of nuclear-nuclear collisions of light projectiles and/or targets

Final state models to determine exact interaction process and sec… particle p…
- … …e …brium

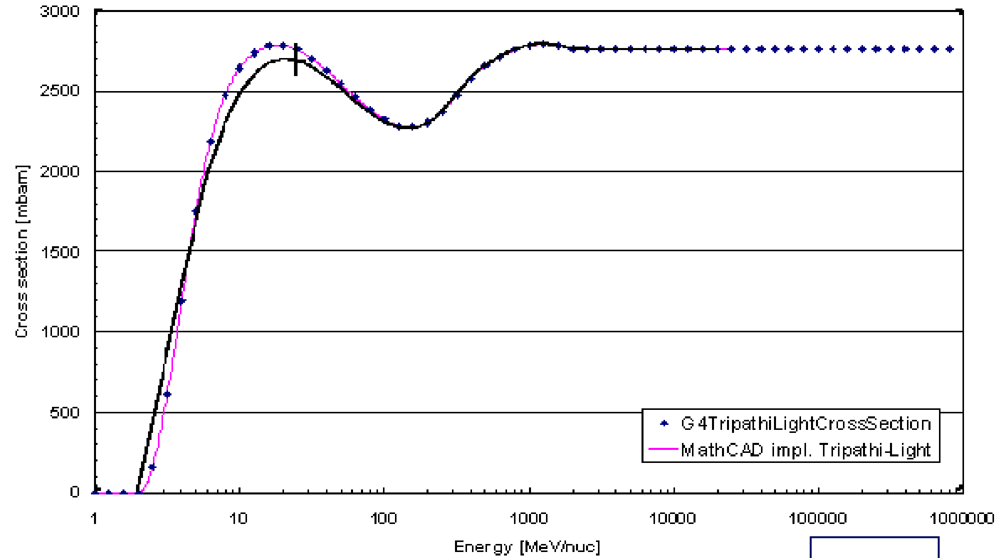
Abrasion (macroscopic) and ablation model, and electromagnetic dissociation model



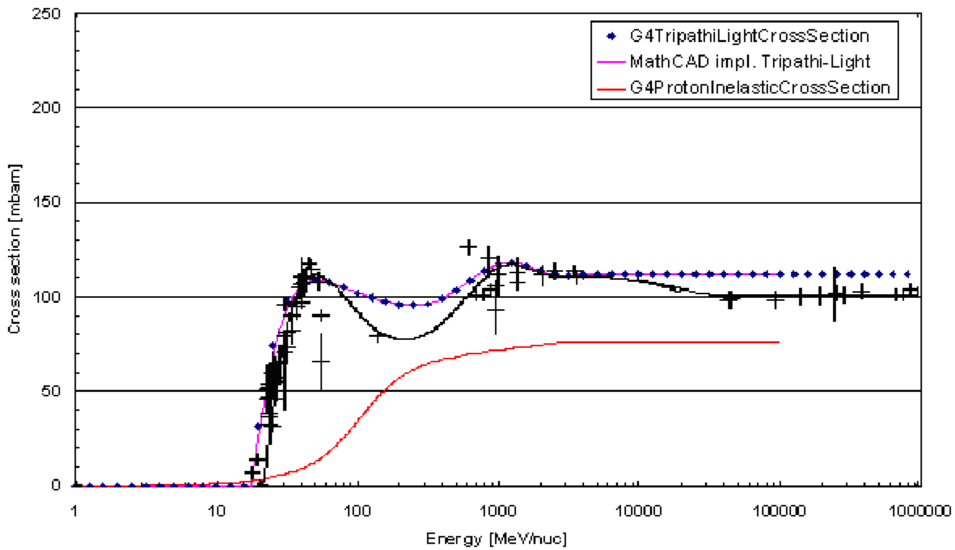
Total cross-section models allow rapid determination of mean-free paths, but cannot determine momentum change and secondary particle production α-Al



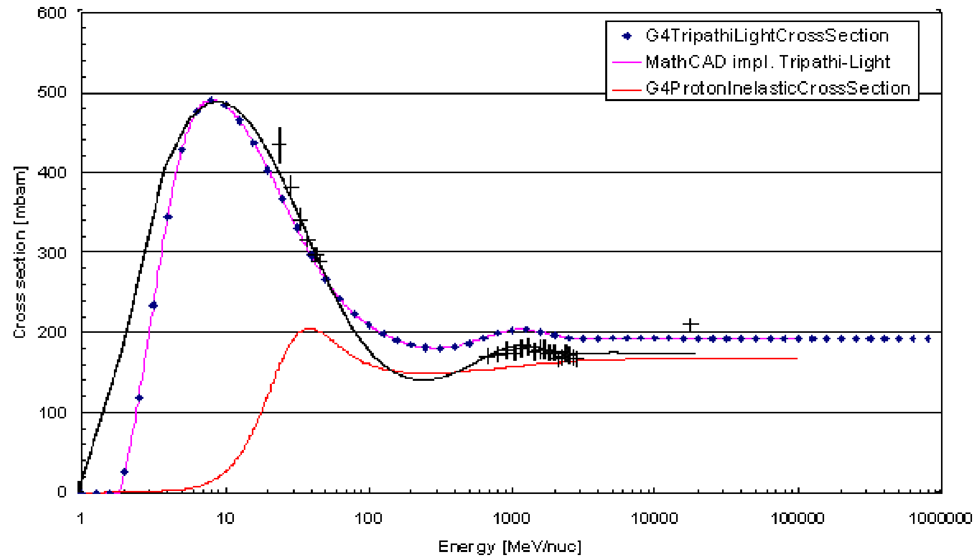
α-Ta



p-α

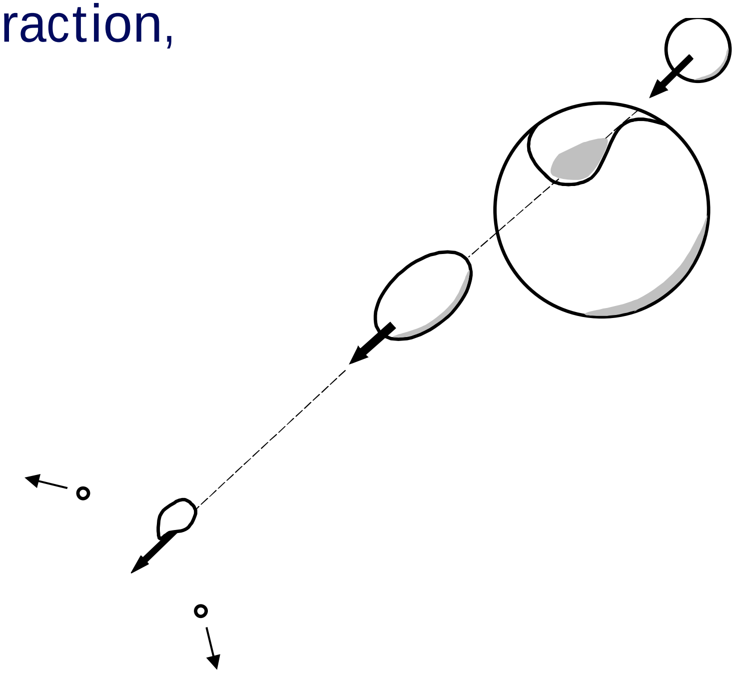


p-Li



Final State - NASA NUCFRG2 Abrasion

- ***Macroscopic*** model for nuclear-nuclear interaction, rather than ***microscopic*** as in Binary and Classical Cascade, or JQMD
- Interaction region determined from geometric arguments
- Nuclear density assumed constant
- Number of “participants” in the overlap region based on approximation for nucleon mean-free path and maximum chord-length in the overlap region



- NASA model follows this with ablation process - excitation energy from:
  - excess surface area of nuclear fragments
  - average energy transferred to nucleons which do not escape the nuclear fragment

G4WilsonAbrasionModel

- In principle the abrasion model should provide advantages in speed over microscopic simulation
- Replace ablation process with Geant4 de-excitation models (evaporation, Fermi break-up, multi-fragmentation, and photo-evaporation) … *later reconsidered*
- Abraded nucleons from projected and target nucleus treated, as well as de-excitation of projectile and target pre-fragments
- By-product of implementation is a Geant4 class for microscopic model to account for excitation as a result of nuclear asphericity

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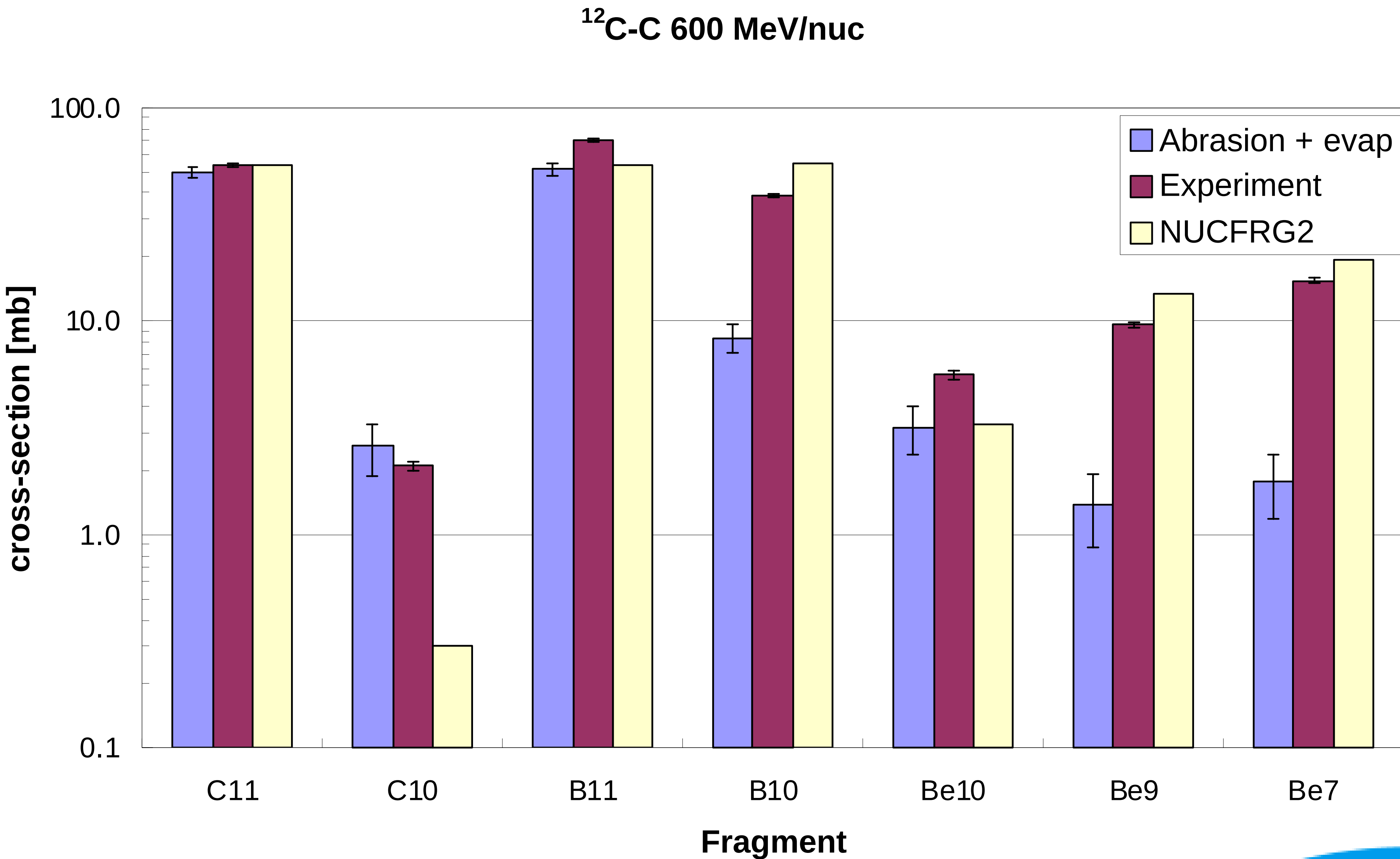
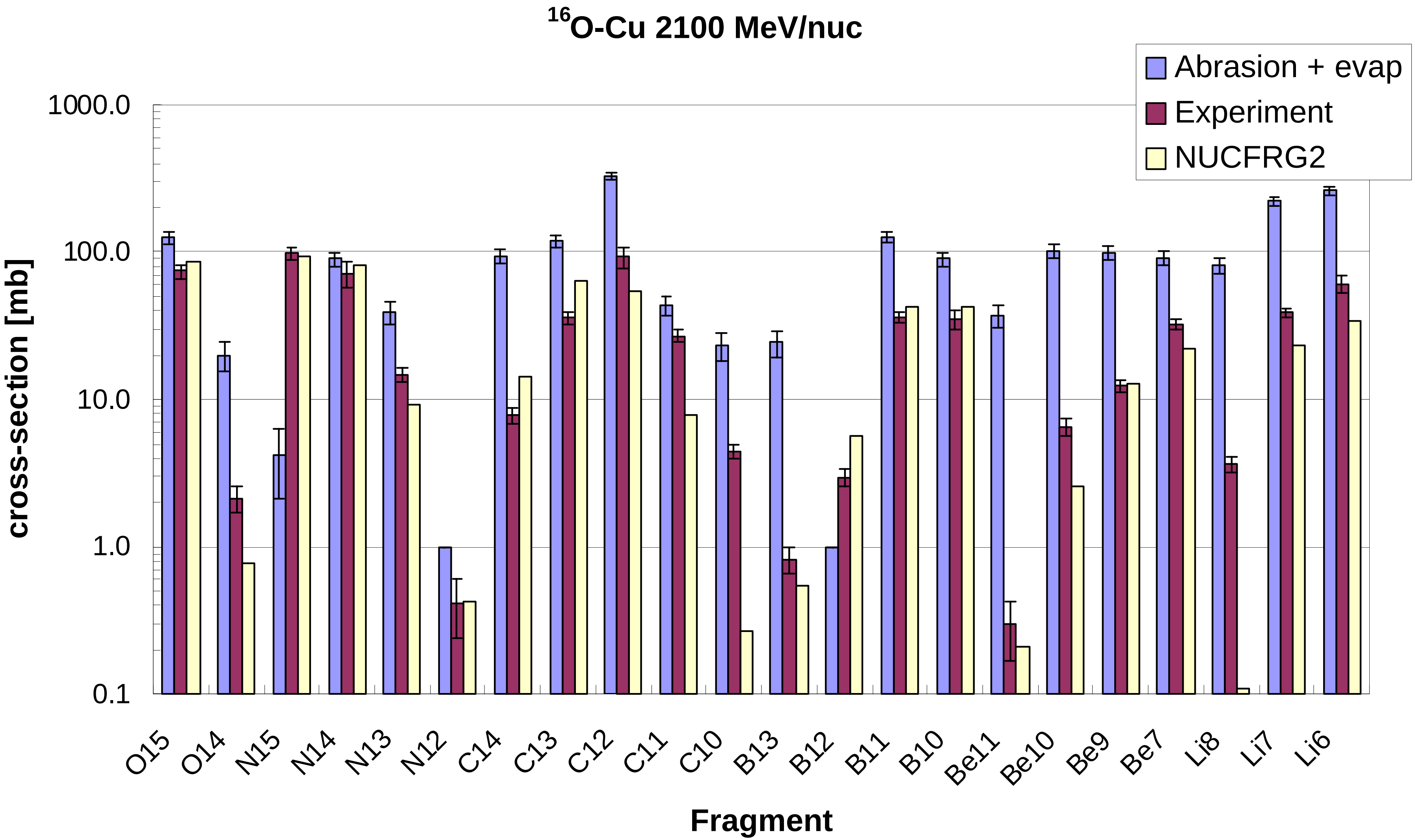


^{12}C-C 600 MeV/nuc
100.0
10.0
1.0
0.1
cross-section [mb]
Abrasion + evap
Experiment
NUCFRG2
C11
C10
B11
B10
Be10
Be9
Be7
Fragment

QinetiQ



^{16}O-Cu 2100 MeV/nuc
Abrasion + evap
Experiment
NUCFRG2
1000.0
100.0
10.0
1.0
0.1
cross-section [mb]
O15
O14
N15
N14
N13
N12
C14
C13
C12
C11
C10
B13
B12
B11
B10
Be11
Be10
Be9
Be7
Li8
Li7
Li6
Fragment

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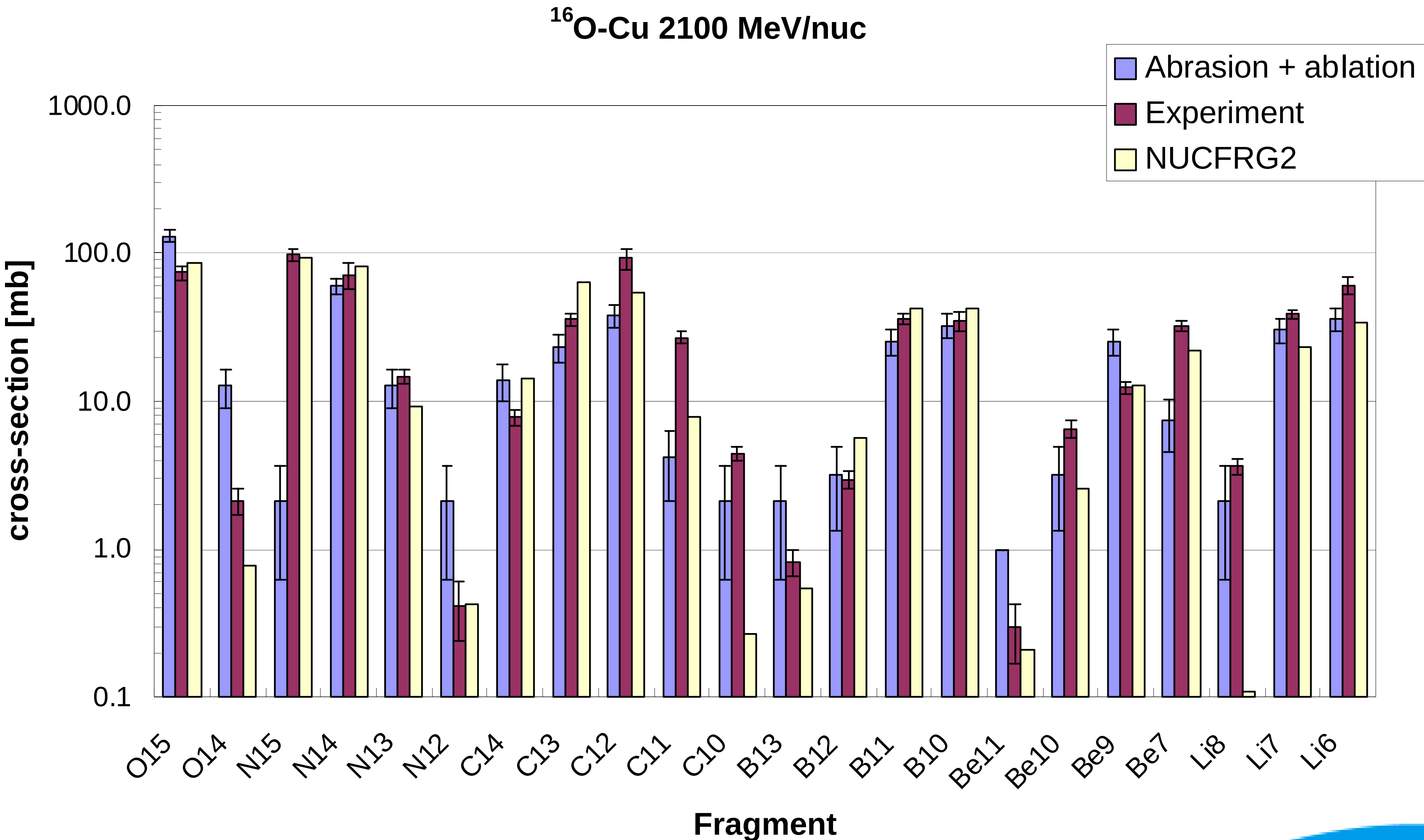

^{16}O-Cu 2100 MeV/nuc
Abrasion + ablation
Experiment
NUCFRG2
1000.0
100.0
10.0
1.0
0.1
cross-section [mb]
O15
O14
N15
N14
N13
N12
C14
C13
C12
C11
C10
B13
B12
B11
B10
Be11
Be10
Be9
Be7
Li8
Li7
Li6
Fragment

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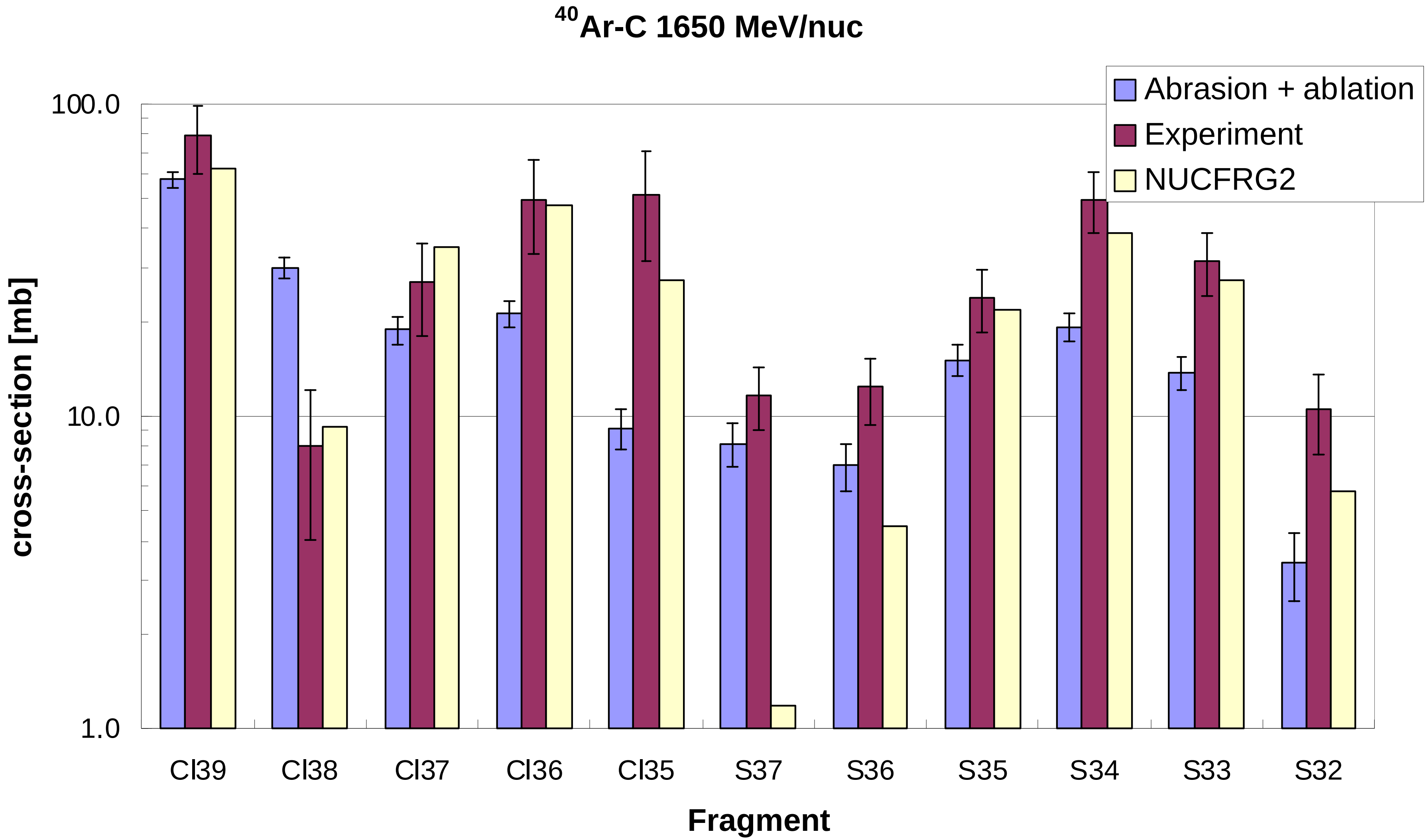

^{40}Ar-C 1650 MeV/nuc
Abrasion + ablation
Experiment
NUCFRG2
cross-section [mb]
100.0
10.0
1.0
Cl39
Cl38
Cl37
Cl36
Cl35
S37
S36
S35
S34
S33
S32
Fragment

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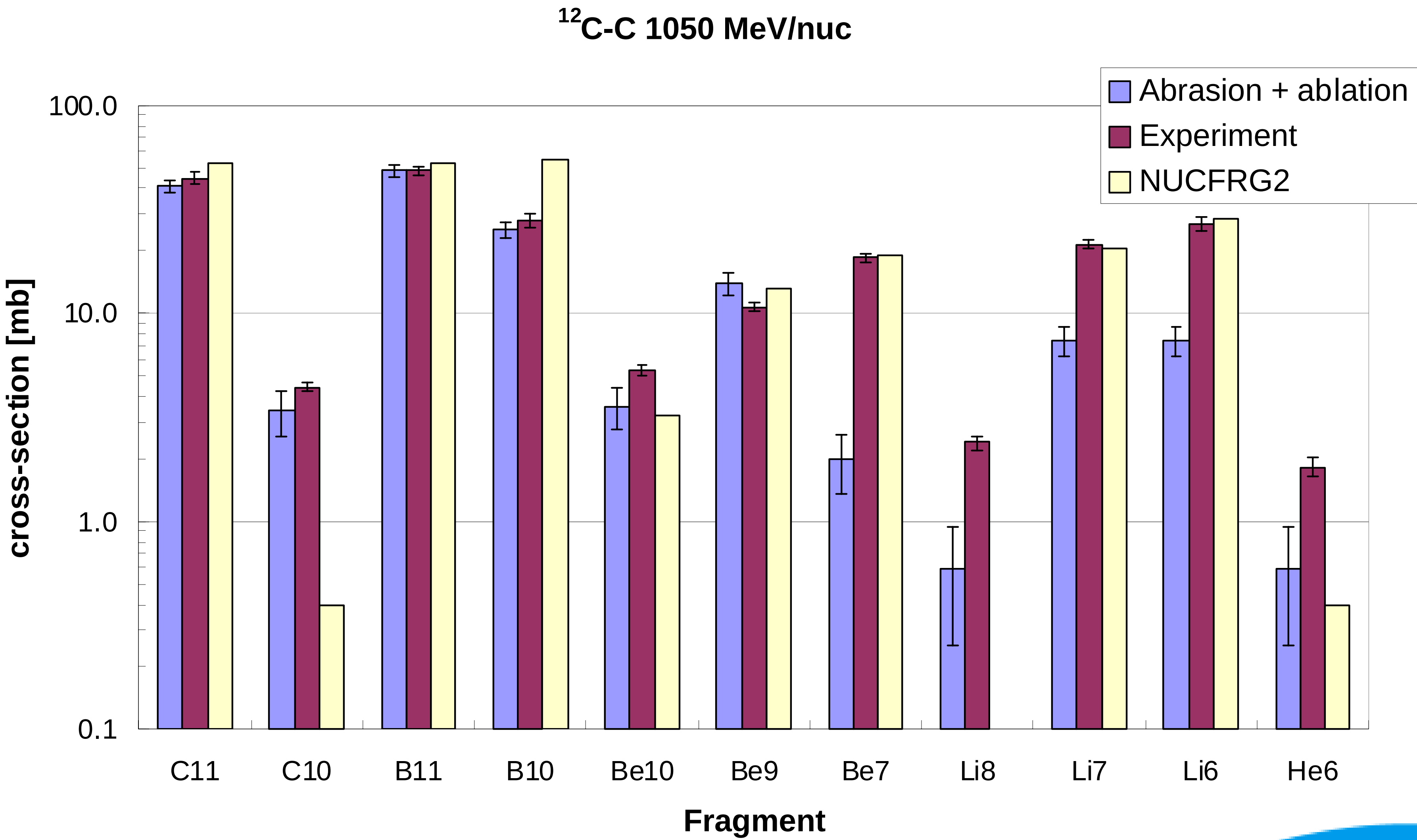
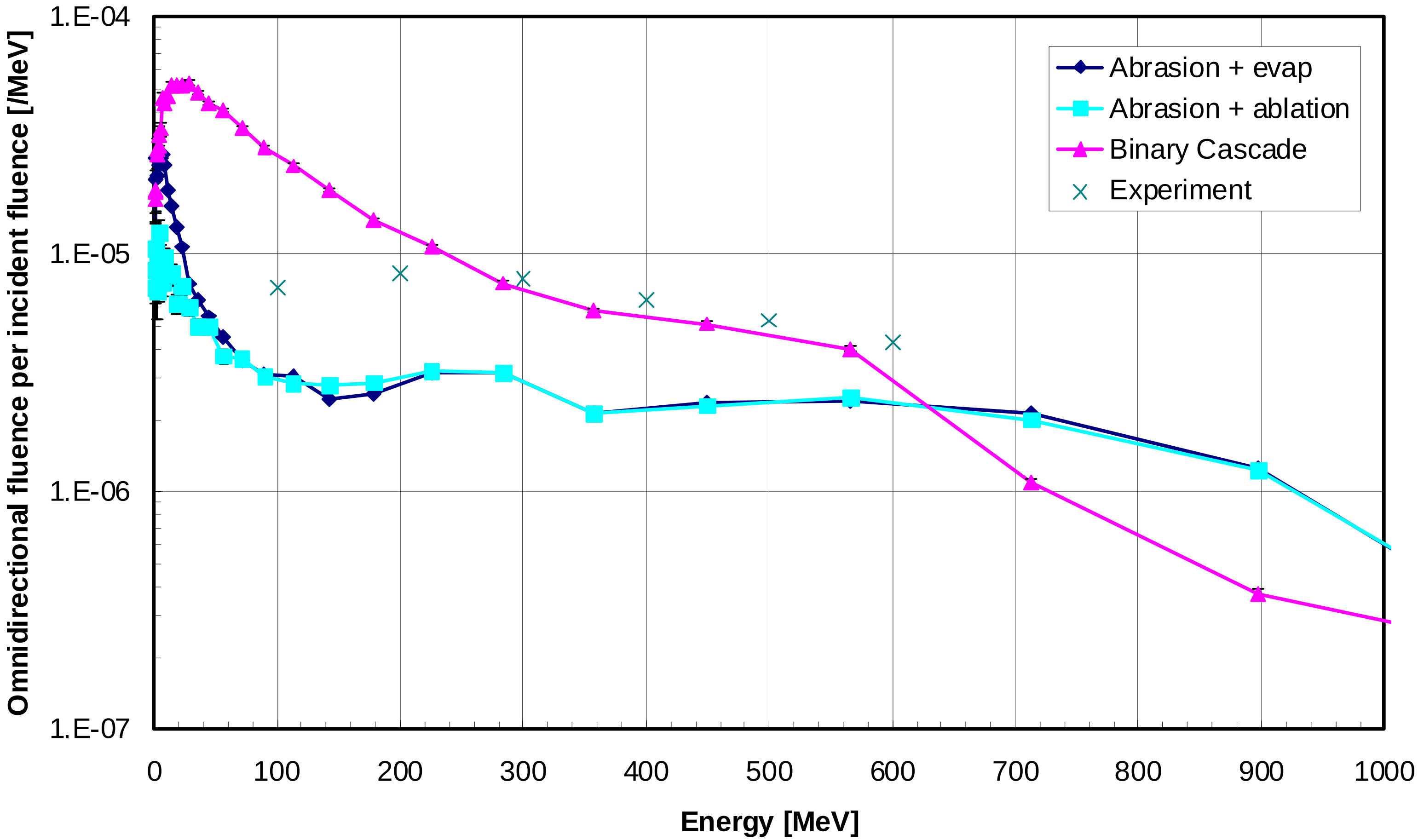


^{12}C-C 1050 MeV/nuc
Abrasion + ablation
Experiment
NUCFRG2
cross-section [mb]
100.0
10.0
1.0
0.1
C11
C10
B11
B10
Be10
Be9
Be7
Li8
Li7
Li6
He6
Fragment

Comparison of secondary proton spectrum (at 30°) predicted by abrasion and binary cascade models, and experimental data for 800MeV/nuc ^{20}Ne incident on ^{20}Ne



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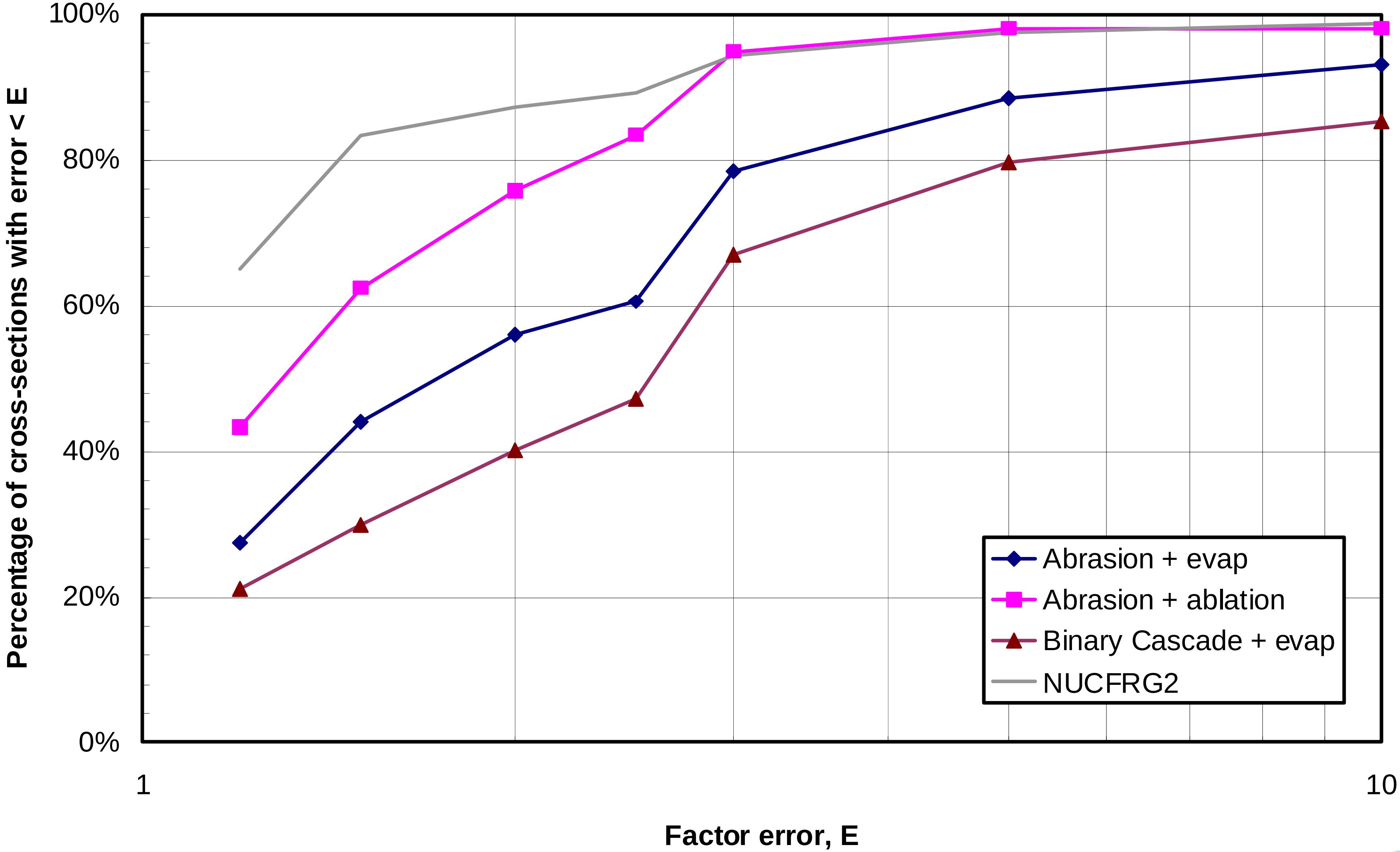
Comparison of the percentage of times the predicted cross-section for fragment production is within a factor of E of the experimental value (for various projectile nuclei on carbon target).



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Execution Time

- G4WilsonAbrasionModel offers improved simulation speed compared with Binary Cascade model
- Simulation of 100,000 ions incident on 5mm ^{12}C:

Projectile	*G4WilsonAbrasionModel*	*G4BinaryLightIonReaction*
^{40}Ar (2632 AMeV)	*107s*	*577s*
^{12}C (8773 AMeV)	*46s*	*196s*

Nuclear EM Dissociation

- Liberation of nucleons or nuclear fragments as a result of electromagnetic field, rather than the strong nuclear force
- Important for relativistic nuclear-nuclear interaction, *e.g.* for 3.7GeV/nucleon ^{28}Si projectiles in Ag, ED accounts for ~25% of the nuclear interaction events
- NASA model used in HZEFRG and NUCFRG2 predict ED events for 1st and 2nd moments of electric field and cross-sections for giant dipole / quadrupole resonances (watch out for errors though)

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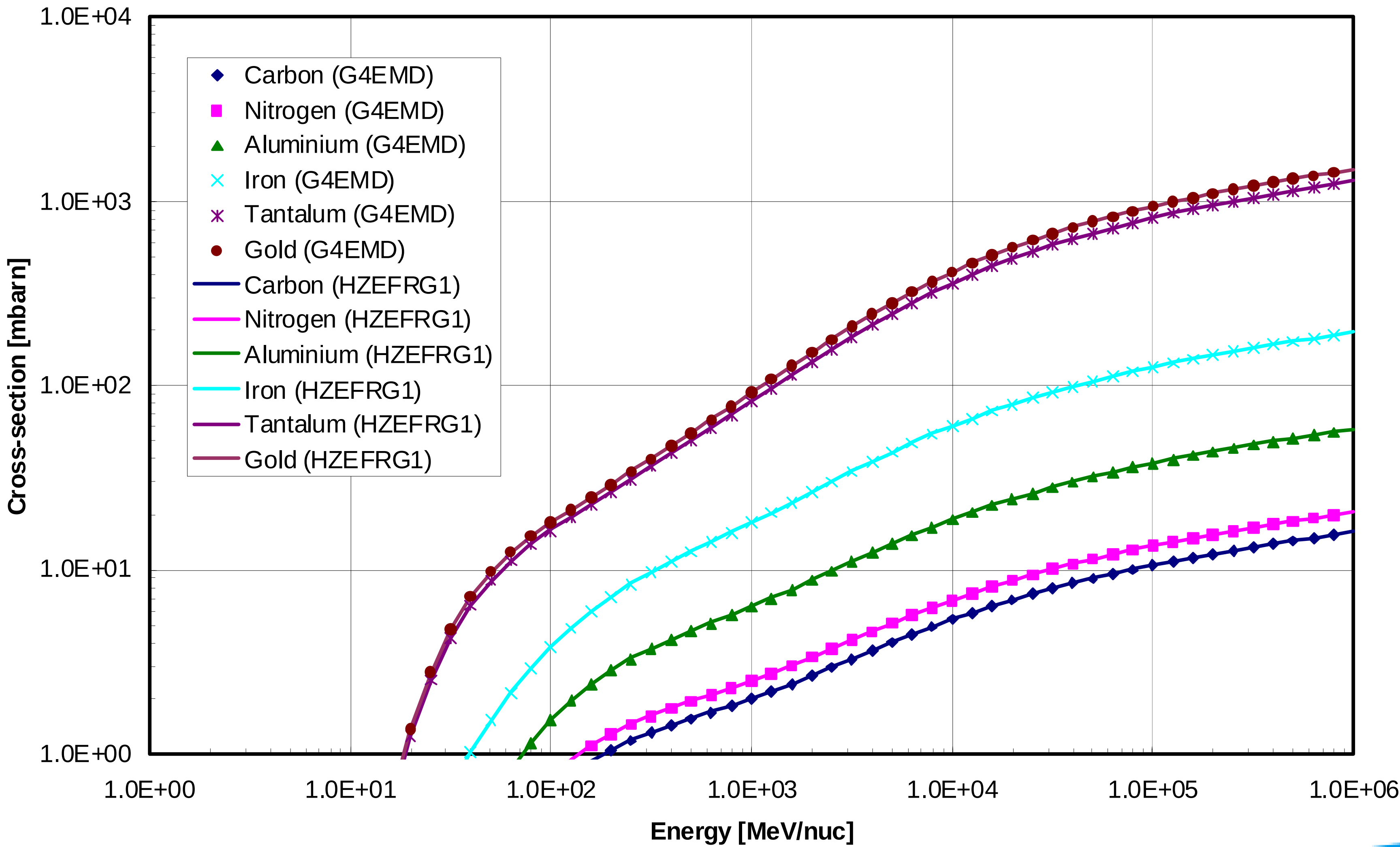
Nuclear EM Dissociation

- The G4EMDissociation model is an implementation of the NUCFRG2 physics
- Applied for dissociation of projectile ***and*** target
- Note however that other nuclear fragments can also be produced but difficulty is getting cross-sections for those fragment production to integrate over virtual photon spectrum

$$N_{E1}\left(E_\gamma\right)=\frac{2\alpha Z_T^2}{\pi\beta^2 E_\gamma}\left\{\xi k_0(\xi)k_1(\xi)-\frac{\xi^2\beta^2}{2}\left(k_1^2(\xi)-k_0^2(\xi)\right)\right\}$$

$$N_{E2}\left(E_\gamma\right)=\frac{2\alpha Z_T^2}{\pi\beta^4 E_\gamma}\left\{2\left(1-\beta^2\right)k_1^2(\xi)+\xi\left(2-\beta^2\right)k_0(\xi)k_1(\xi)-\frac{\xi^2\beta^4}{2}\left(k_1^2(\xi)-k_0^2(\xi)\right)\right\}$$

Comparison of G4EMDissociationCrossSection and HZEFRG1 predictions for EMD cross-section of ^{12}C incident on a variety of targets.



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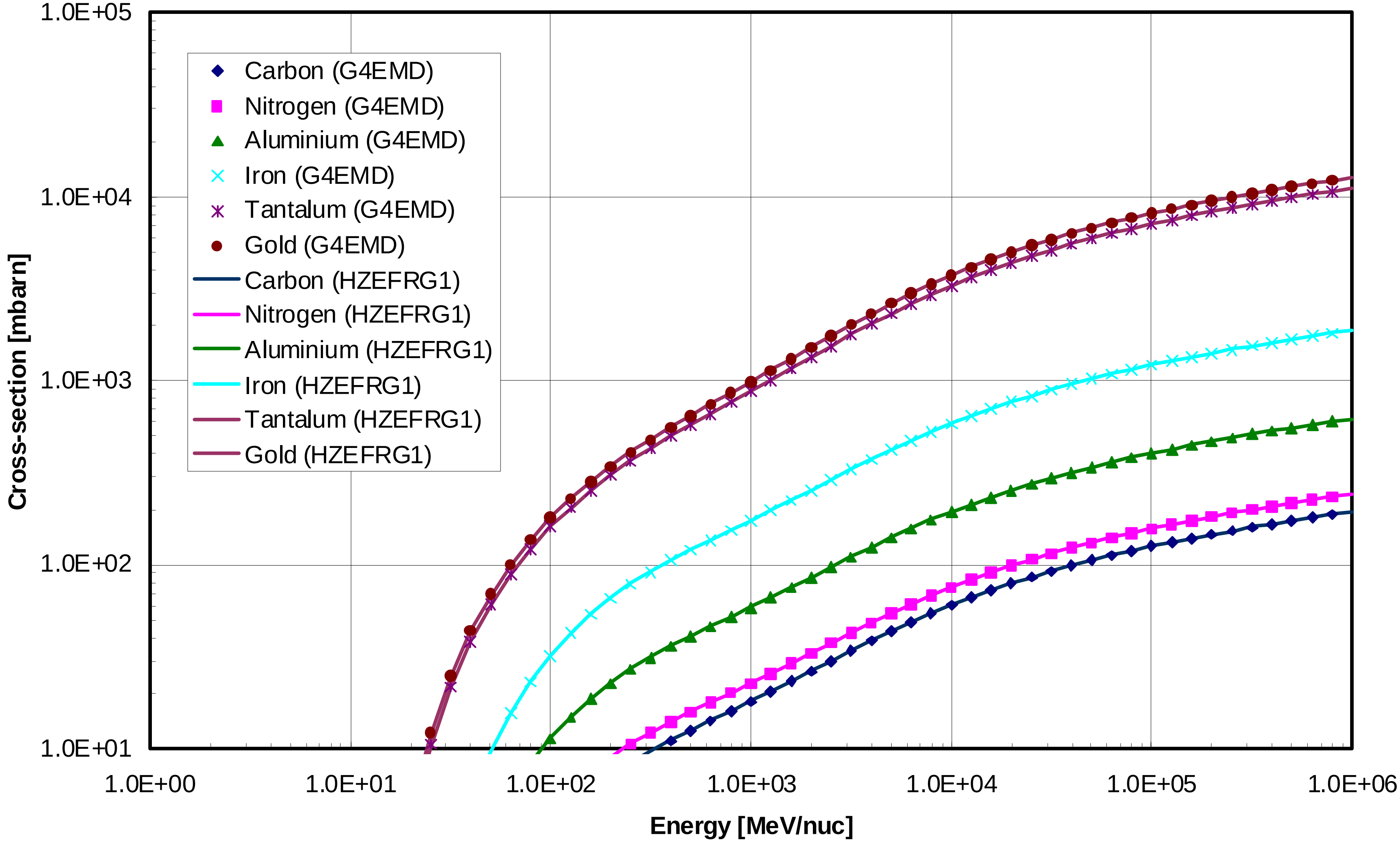
Comparison of G4EMDissociationCrossSection and HZEFRG1 predictions for EMD cross-section of ^{56}Fe incident on a variety of targets.



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G4EMDissociation

$^{28}Si(14.5GeV/n,^{107}Ag) \rightarrow {}^{27}Al + p$

G4EMDissociation	Experiment
216 ± 2 mb	165 ± 24 mb
	128 ± 33 mb

$^{16}O(200GeV/n, {}^{107}Ag) \rightarrow {}^{15}N + p$

G4EMDissociation	Experiment
331 ± 2 mb	293 ± 39 mb
	342 ± 22 mb

$^{24}Mg(3.7GeV/n, {}^{107}Ag) \rightarrow {}^{23}Na + p$

G4EMDissociation	Experiment
124 ± 2 mb	154 ± 31 mb

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IONMARSE

- Classes implemented:
  - ***G4TripathiLightCrossSection***: improved total inelastic cross-section model for protons and light nuclear projectiles/target
  - ***G4ESAGeneralNNInelasticCrossSection***: General cross-section model selector for proton/nuclear-nuclear interactions
  - ***G4WilsonAbrasionModel*** : Abrasion (macroscopic) interaction model
  - ***G4WilsonAblationModel***: Ablation+evaporation model as an alternative to standard Geant4 de-excitation (evaporation / break-up / fission)
  - ***G4EMDissociation***: Electromagnetic dissociation model

Experimental Data for N-N Interactions

- Large amount of data for heavy target nuclei such as silver, gold, lead, bismuth and depleted uranium - not as relevant to space
- Some information on double differential cross-sections for lighter nuclei, including the sources of data used by Yariv and Fraenkel

No	Reference	Source particles	Target material	Quantities measured
1	T Kato, *et al*, "Systematic analysis of neutron yields from thick targets bombarded by heavy ions and protons with moving source model," *Nucl Instrum Meth Phys Res*, **A480**, 571-590, 2002.	C @ 100, 180, and 400 MeV/nucleon Ar @ 400 MeV/nucleon Fe @ 400 MeV/nucleon Xe @ 400 MeV/nucleon	C, Al, Cu, Pb	DDCS for neutrons
2	H Sato *et al*, JAERI Conference 2000-005, 261, Proceedings of the 1999 Symposium on Nuclear Data, 18-19 November 1999, Jaeri, Japan, 2000.	C @ 135 MeV/nucleon	C, Al, Cu, Pb	DDCS
3	T Kurosawa *et al*, " Neutron yields from thick C, Al, Cu, and Pb targets bombarded by 400 MeV/nucleon Ar, Fe, Xe and 800 MeV/nucleon Si ions," *Phys Rev*, **C62**, 44615-44625, 2000.	Ar, Fe, Xe 400 MeV/nucleon Si, 800 MeV/nucleon	C, Al, Cu, Pb	DDCS
4	T Kurosawa *et al*, *Nucl Sci Eng*, **132**, 30, 1999.	C @ 100 MeV/nucleon 180 MeV/nucleon and 400 MeV/nucleon He @ 180 MeV/nucleon	C, Al,Cu, Pb	DDCS
5	D. Hilscher, et al, "Neutron production by hadron-induced spallation reactions in thin and thick Pb and U targets from 1 to 5 GeV," *Nucl Instrum Meth Phys Res*, **A414**, 100-116, 1999.	p, $\bar{p}$, K and (some) d, @ 1-5 GeV	Pb, U	Neutron multiplicity
6	B Lott, *et al*, "Neutron multiplicity distributions for 200 MeV proton-, deuteron- and ^{4}He-induced spallation reactions in thick Pb targets," *Nucl Instrum Meth Phys Res*, **A414**, 117-124, 1999.	^{1}H @ 197MeV proton ^{2}H @ 188MeV ^{4}He @ 214MeV	Pb	Neutron multiplicity (questionable value due to lack of normalisation?)
7	B M Quednau, *et al*, " Decay patterns of target-like and projectile-like nuclei produced in ^{84}Kr + ^{197}Au, ^{nat}U reactions at E/A = 150 MeV," *Nucl Phys*, **A606**, 538-558, 1996.	^{84}Kr, 150 MeV/nucleon	^{197}Au, natural abundance U	Neutron and alpha multiplicity

Table 1: Bibliography of experimental data sources on nuclear-nuclear interactions (part 1).

- Data being used to validate new models

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Summary

- Reviewed available models and data for nuclear-nuclear interactions
- Implemented improved models for total inelastic cross-sections in Geant4
- Implemented macroscopic nuclear-nuclear final state model similar to NASA's NUCFRG2
  - This improvement should also allow better determination of nuclear excitation in microscopic models (Binary Cascade)
- Geant4 can now treat EM dissociation interactions, applicable to heavy projectiles or targets

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Other Issues to Address before Applying Geant4 to Interplanetary Missions

- Inclusion of nuclear forces on the projectile/target angular momentum (this would be relevant to low-energy projectiles);
- Validation of relativistic nuclear-nuclear interaction models (based on the QGS model) when they are developed by other members of the Geant4 Hadronics Group.
- Validation of Geant4 fission model for incident particle energies above ~1.2 GeV