Human Research Program Investigators' Workshop &

Space Radiation Investigators' Workshop

Galveston, Texas, February 8 - 11, 2016

Electromagnetic Dissociation Cross Sections for High LET Fragments

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Wednesday February 10, 2016

2:15 - 2:30 pm (15 mins.)

Outline

Introduction

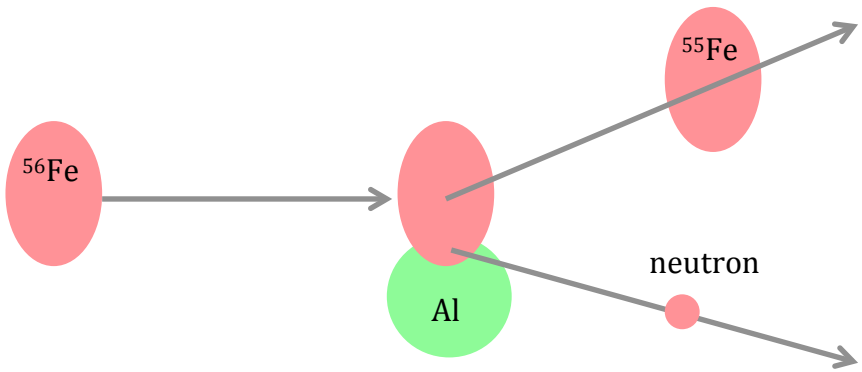
- Galactic cosmic rays (GCR) & solar particle events (SPE) are radiation hazards in space for humans & electronic components
  - GCR contain all nuclei in periodic table
  - Energies hundreds of GeV/nucleon (n) & beyond

- Focus on GCR interactions
  - Nuclei broken into lighter fragments upon interaction with target nuclei

- Target nuclei represent nuclei making up
  - Spacecraft shielding, human body, electronic components, etc.
  - Example: $^{56}\mathrm{Fe} + \mathrm{Al} \rightarrow {}^{55}\mathrm{Fe} + \mathrm{n} + \mathrm{Al}$

Introduction: Strong vs. Electromagnetic (EM)

$$^{56}\mathrm{Fe} + \mathrm{Al} \rightarrow {}^{55}\mathrm{Fe} + \mathrm{n} + \mathrm{Al}$$



Short range strong interaction when projectile & target nuclei overlap.

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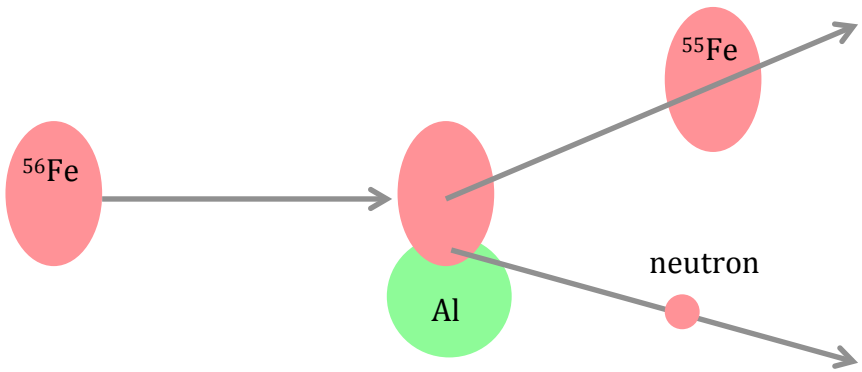

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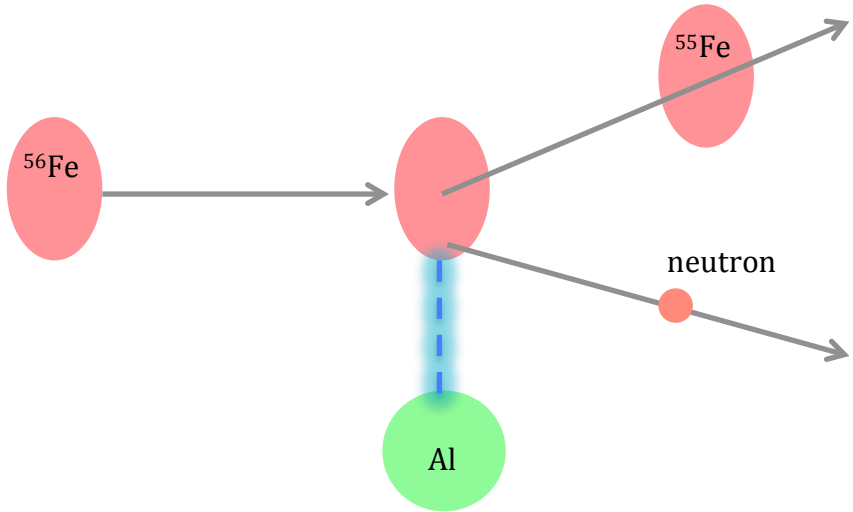
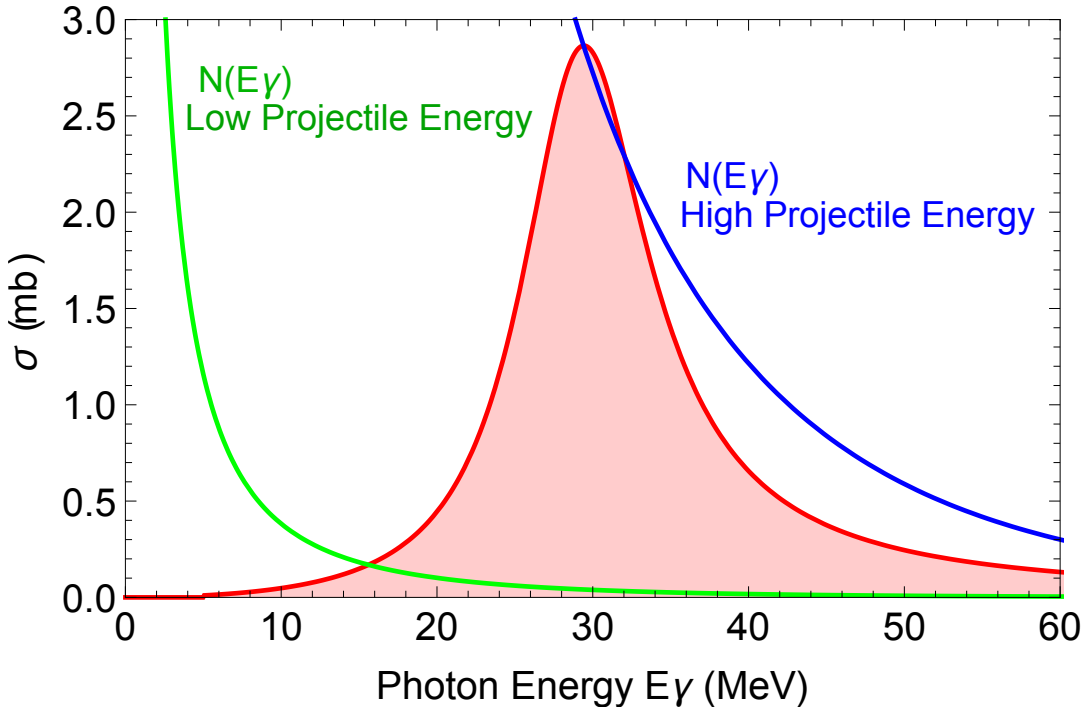


Long range EM interaction when projectile & target nuclei miss each other.

Electromagnetic Dissociation

$$\sigma_{\mathrm{EMD}} = \int dE_\gamma \, N(E_\gamma) \, \sigma(E_\gamma)$$



Photonuclear cross section $\sigma(E_\gamma)$ shown by red curve, plotted against photon energy E_γ.

Green & blue curves show virtual photon spectra $N(E_\gamma)$ for low & high energy projectiles.

Norbury, Nucl. Instr. Meth. Phys. Res. A 703, p. 220, 2013

ELECTROMAGNETIC DISSOCIATION FRAGMENTATION EMDFRG

- Previously, EMD models (e.g. within NUCFRG3) calculate single proton (p) production, single neutron (n) or light ion production
  - Light ion $\equiv$ isotope of hydrogen (H) or helium (He)
  - Deuteron (d $\equiv {}^{2}$H), triton (t $\equiv {}^{3}$H), helion (h $\equiv {}^{3}$He), alpha ($\alpha \equiv {}^{4}$He)

- New model EMDFRG accounts for multiple nucleon production
  - 2p, 2n, 1p1n, 2p1n, 3p1α, 2p2t, ... (in addition to single light ions)
  - Norbury, Nucl. Instr. Meth. Phys. Res. A 703, p. 220, 2013

- Such processes important:
  - Consider reaction ^{56}Fe + Al $\rightarrow {}^{52}$Cr + X + Al high LET ^{52}Cr
  - Most probable EMD particles representing X are 2p2n or ^{4}He
  - ^{56}Fe + Al $\rightarrow {}^{52}$Cr + ^{4}He + Al EMDFRG & NUCFRG3
    $\rightarrow {}^{52}$Cr + 2p2n + Al EMDFRG
  - $\sigma({}^{52}\text{Cr}) = \sigma(\text{2p2n}) + \sigma({}^{4}\text{He})$
  - Production of high LET ^{52}Cr, must include both multiple nucleon production of 2p2n plus light ion production of ^{4}He

RESULTS

Compare:

EMDFRG ——— with photonuclear parameterization for $\sigma(E_\gamma)$

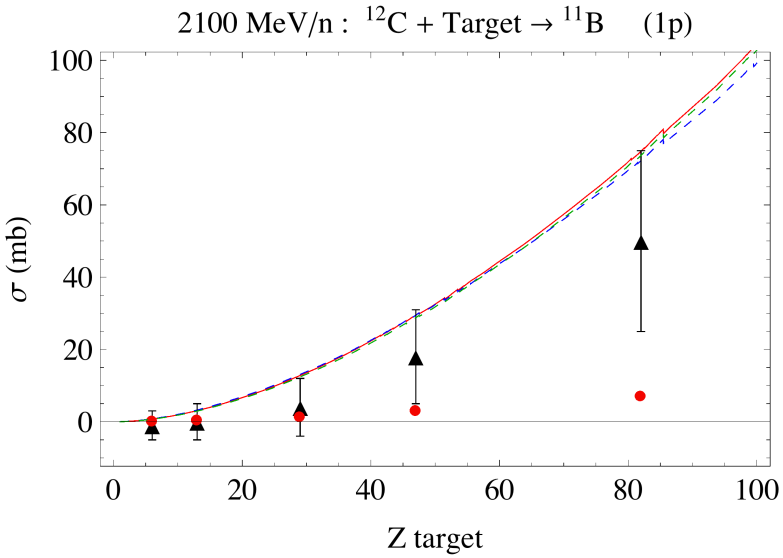
EMDFRG - - - - - - with photonuclear data for $\sigma(E_\gamma)$

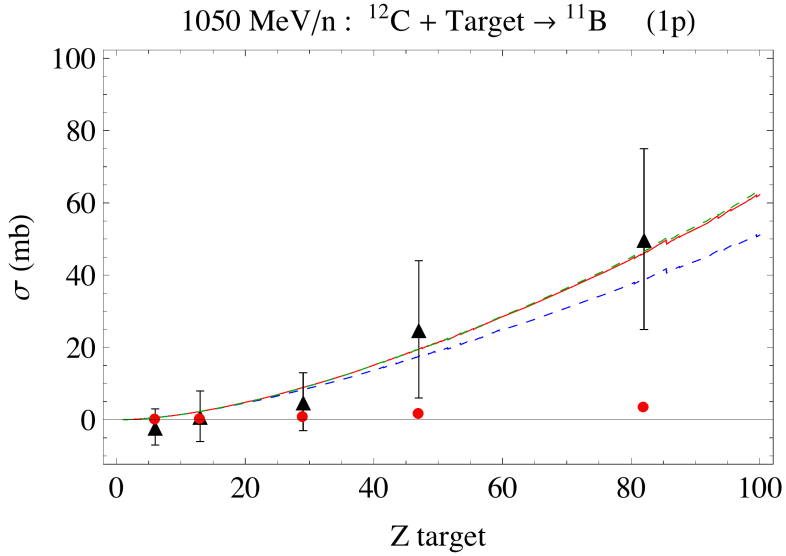
NUCFRG2 - - - - - -

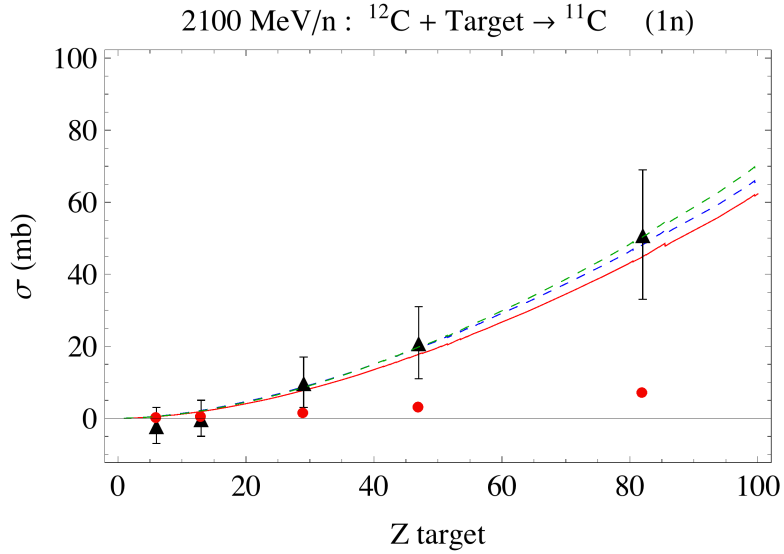
NUCFRG3 .....

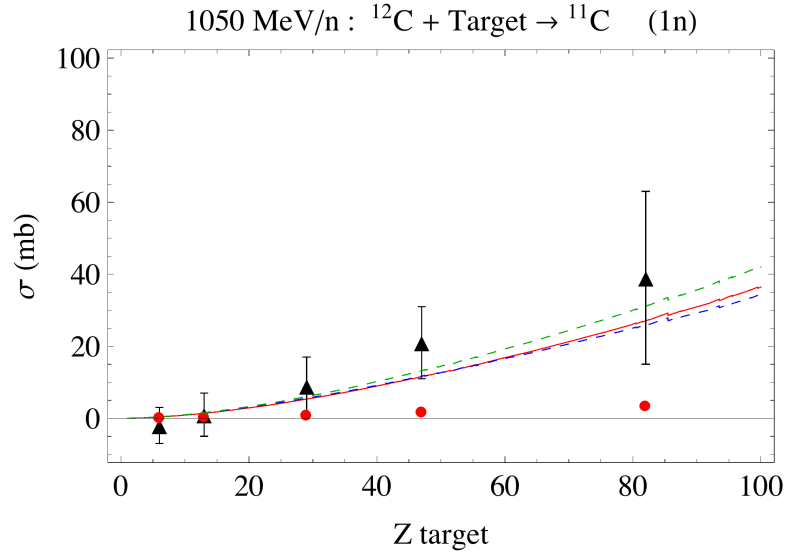
Focus on EMDFRG ——— and NUCFRG3 .....

RESULTS - SINGLE NUCLEON EMDFRG —– DATA - - - NUCFRG2 - - - - NUCFRG3 • • •



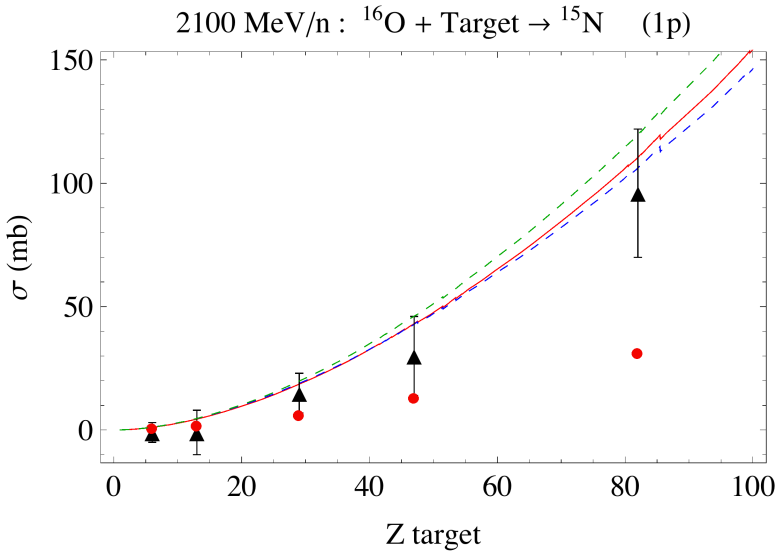


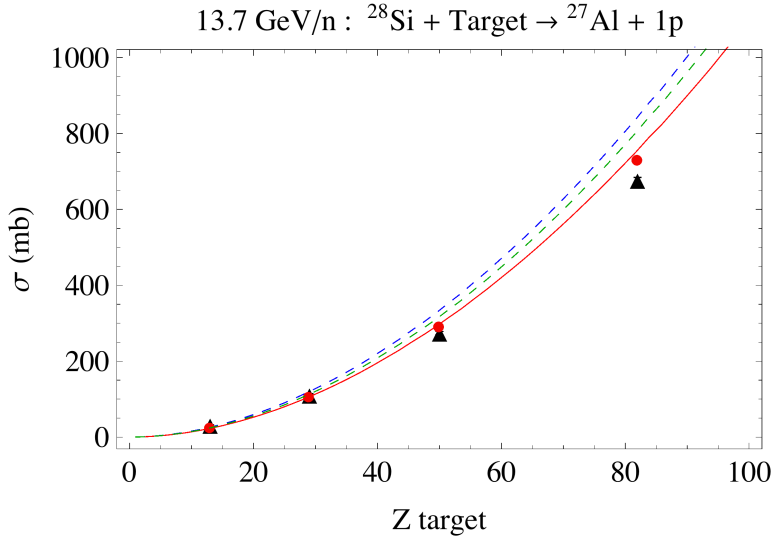


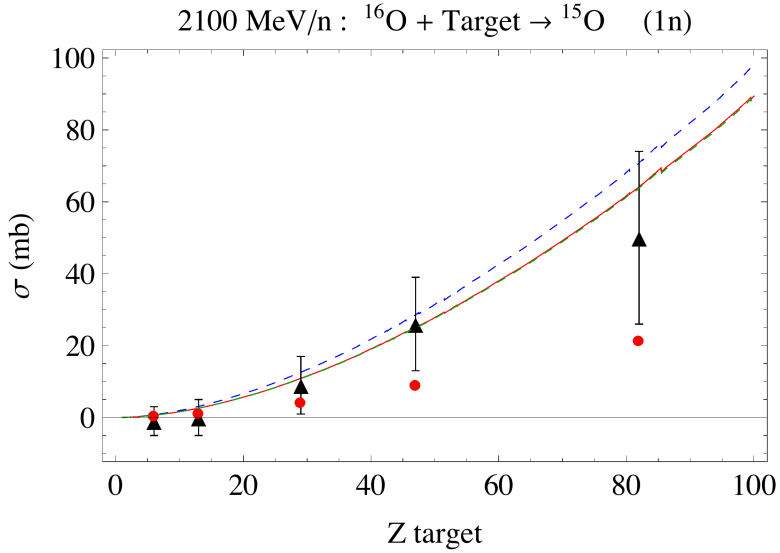


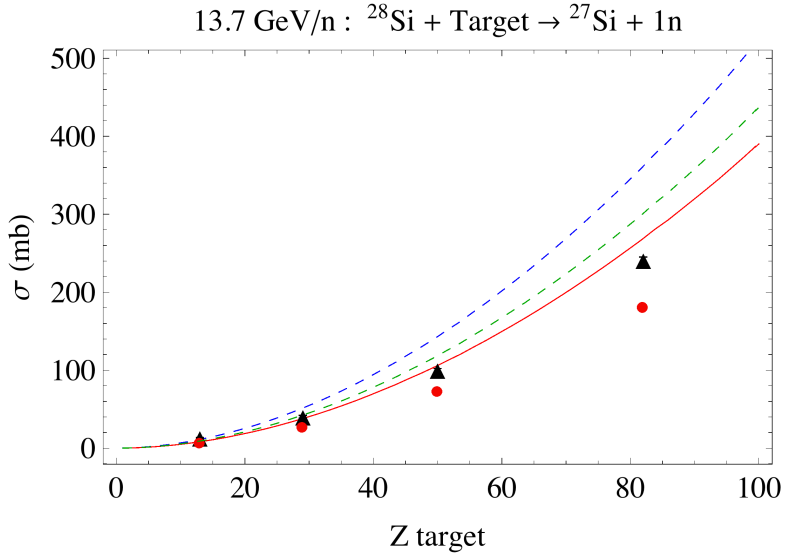
Excellent agreement for EMDFRG ——— Poor agreement for NUCFRG3 • • • • •

RESULTS - SINGLE NUCLEON EMDFRG —– DATA - - - NUCFRG2 - - - - NUCFRG3 • • •









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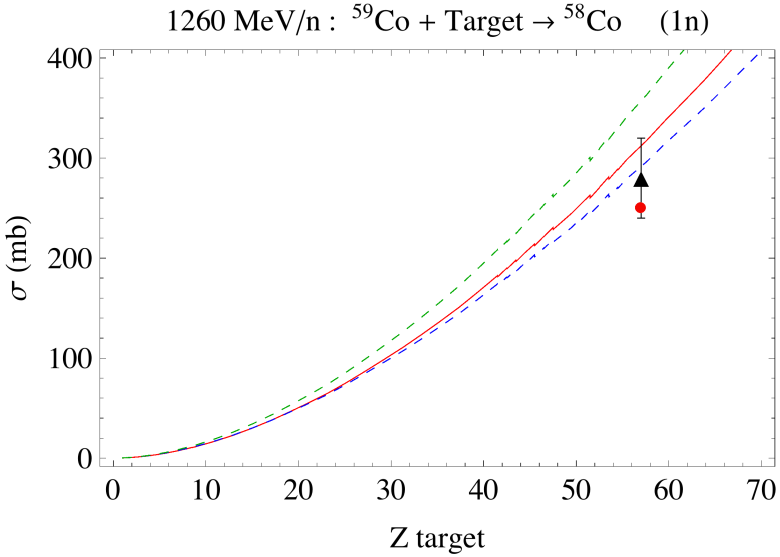
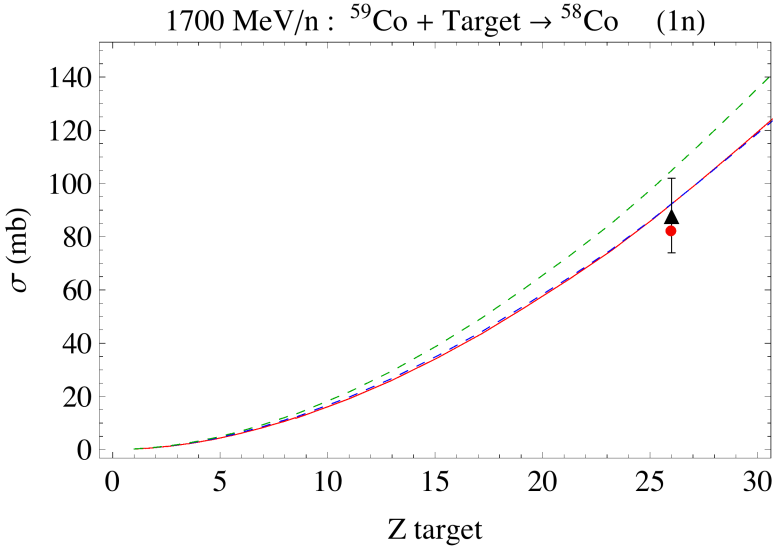
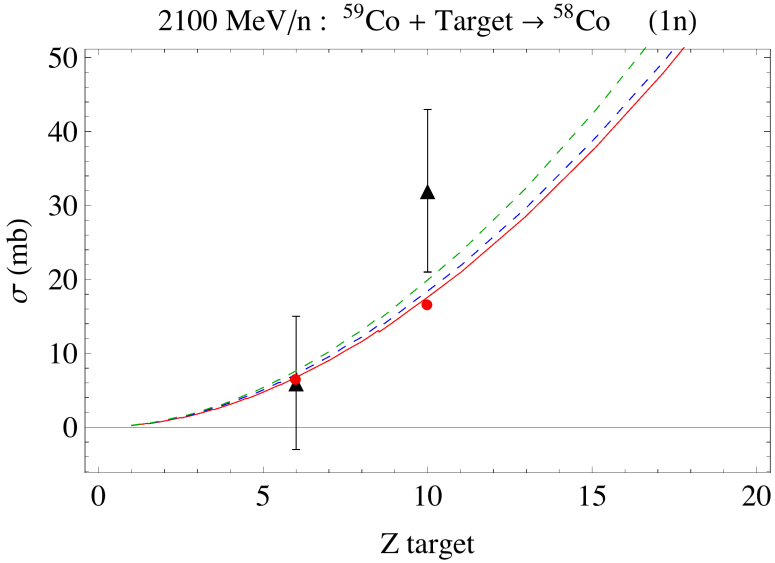
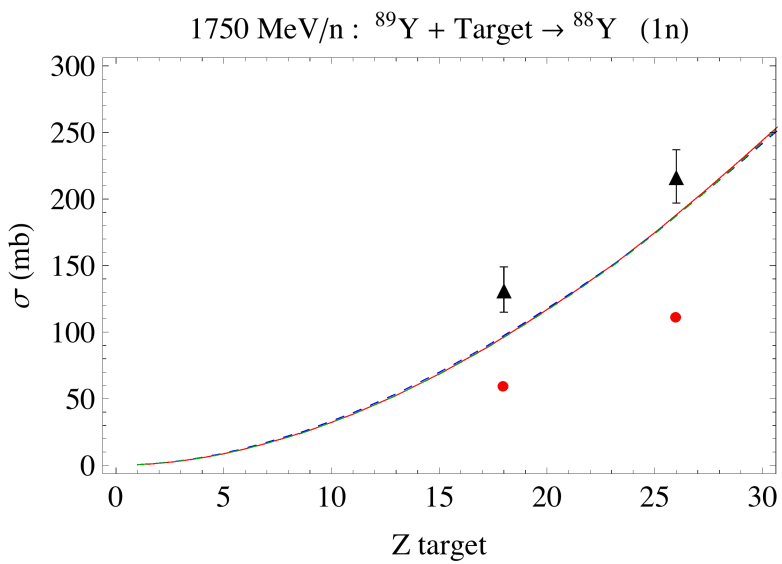


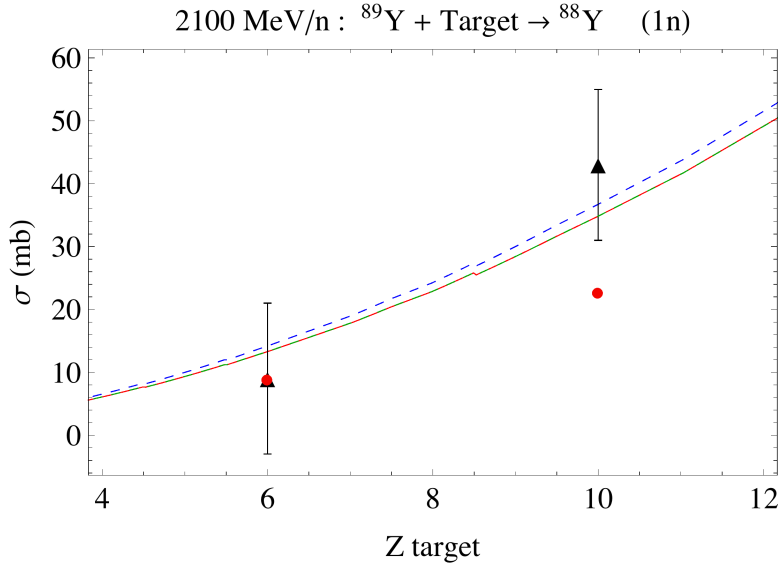


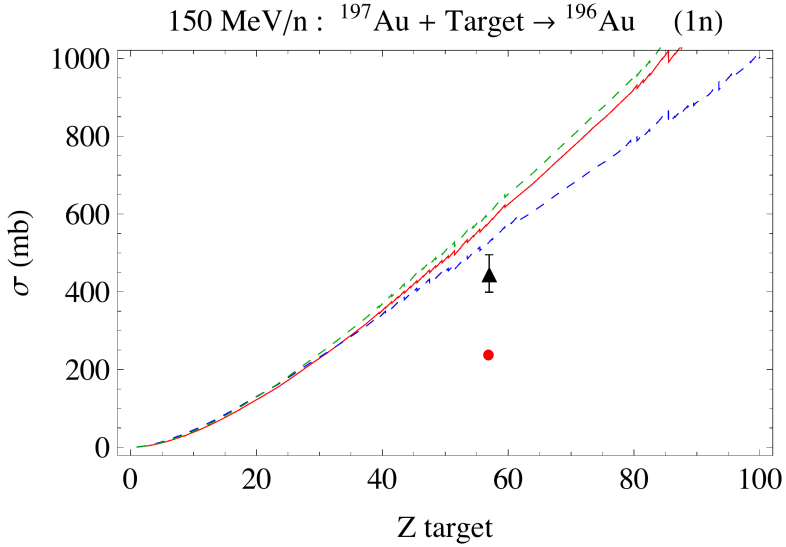


Similar agreement for EMDFRG —— and NUCFRG3 • • • • •

RESULTS - SINGLE NUCLEON EMDFRG —– DATA - - - NUCFRG2 - - - - NUCFRG3 • • •







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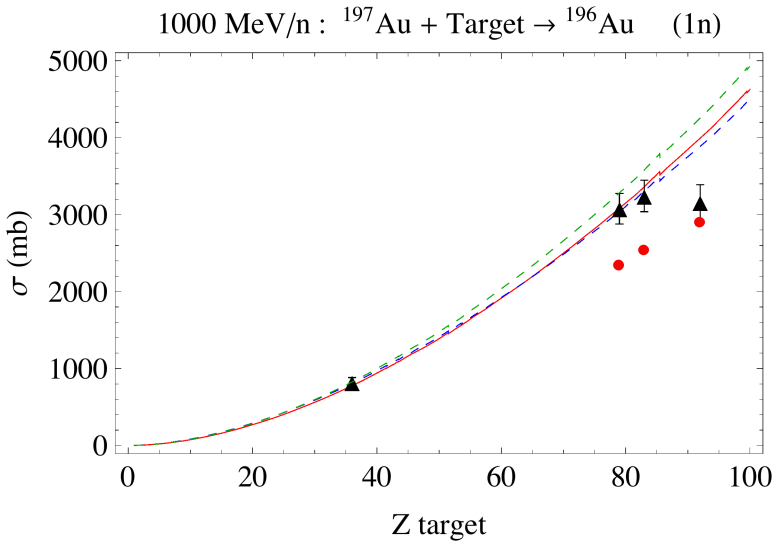
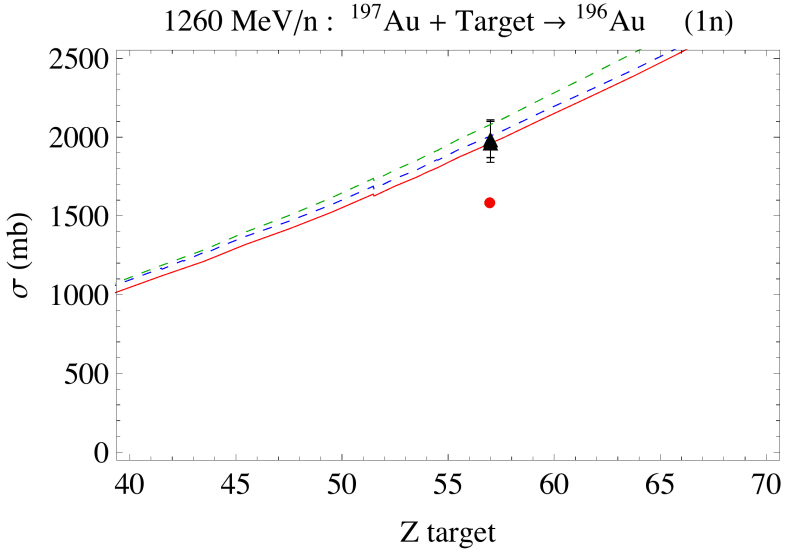
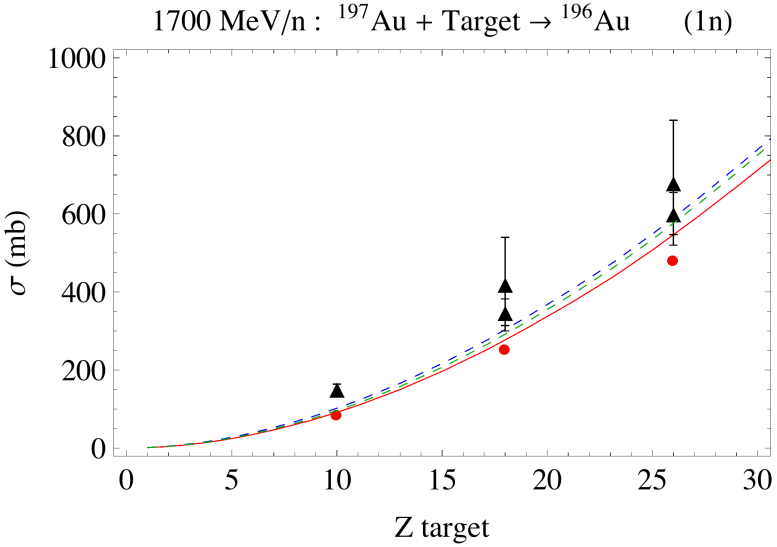
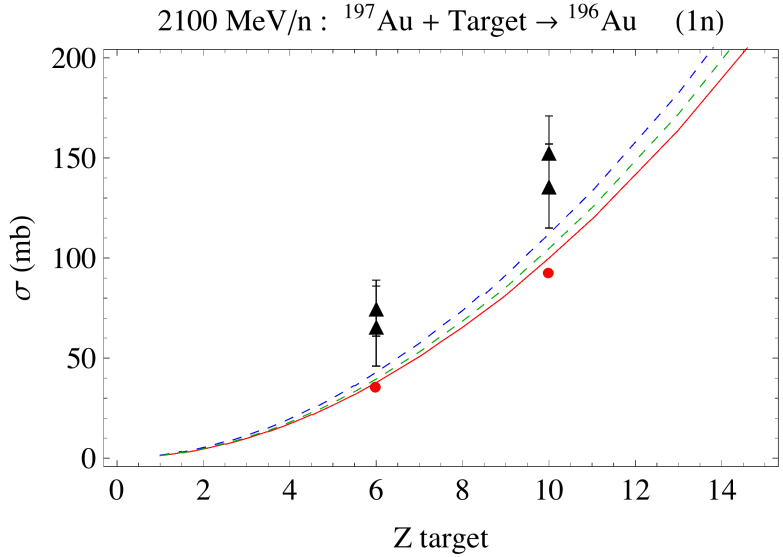
RESULTS - SINGLE NUCLEON EMDFRG —– DATA - - - NUCFRG2 - - - - NUCFRG3 • • •









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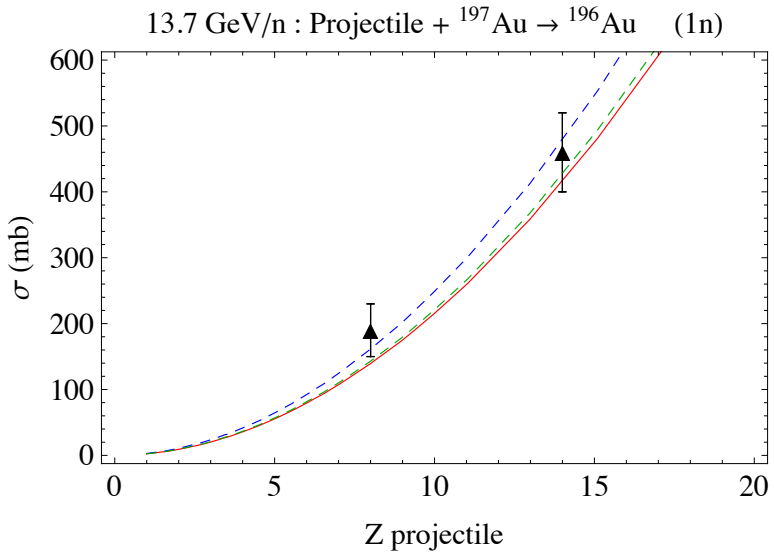
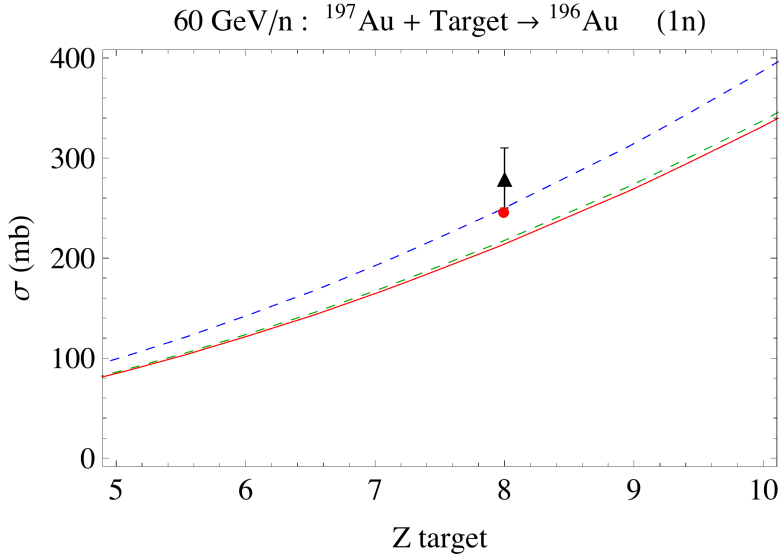
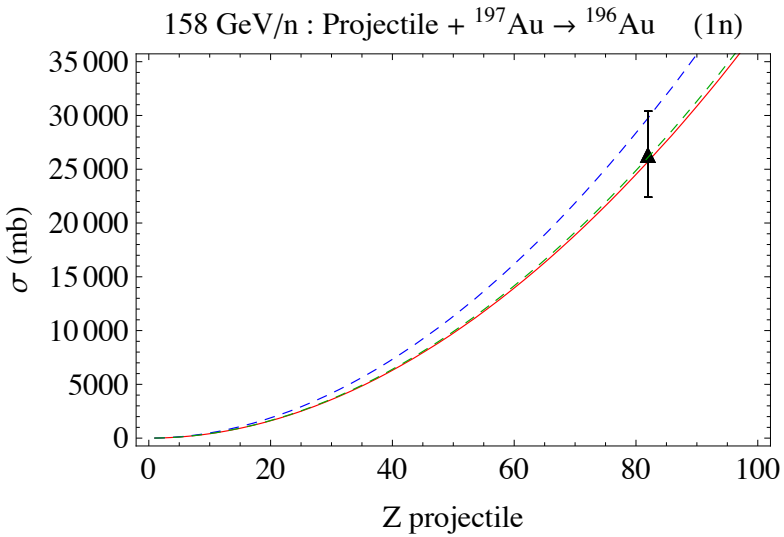
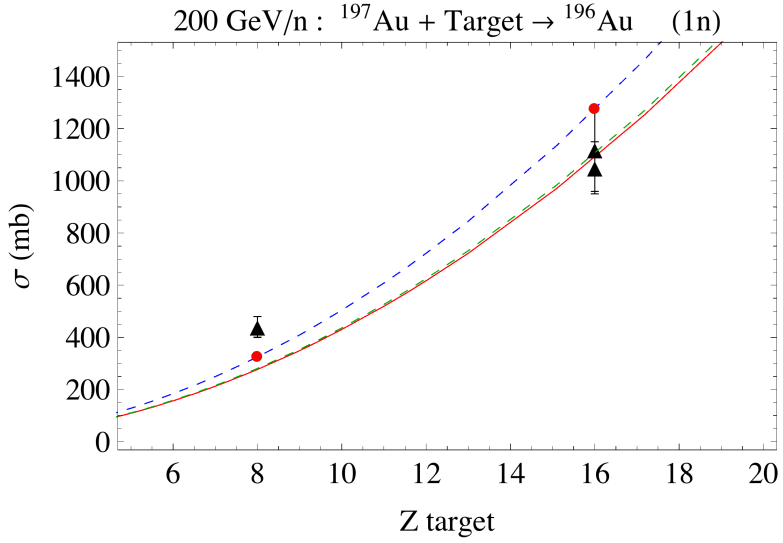


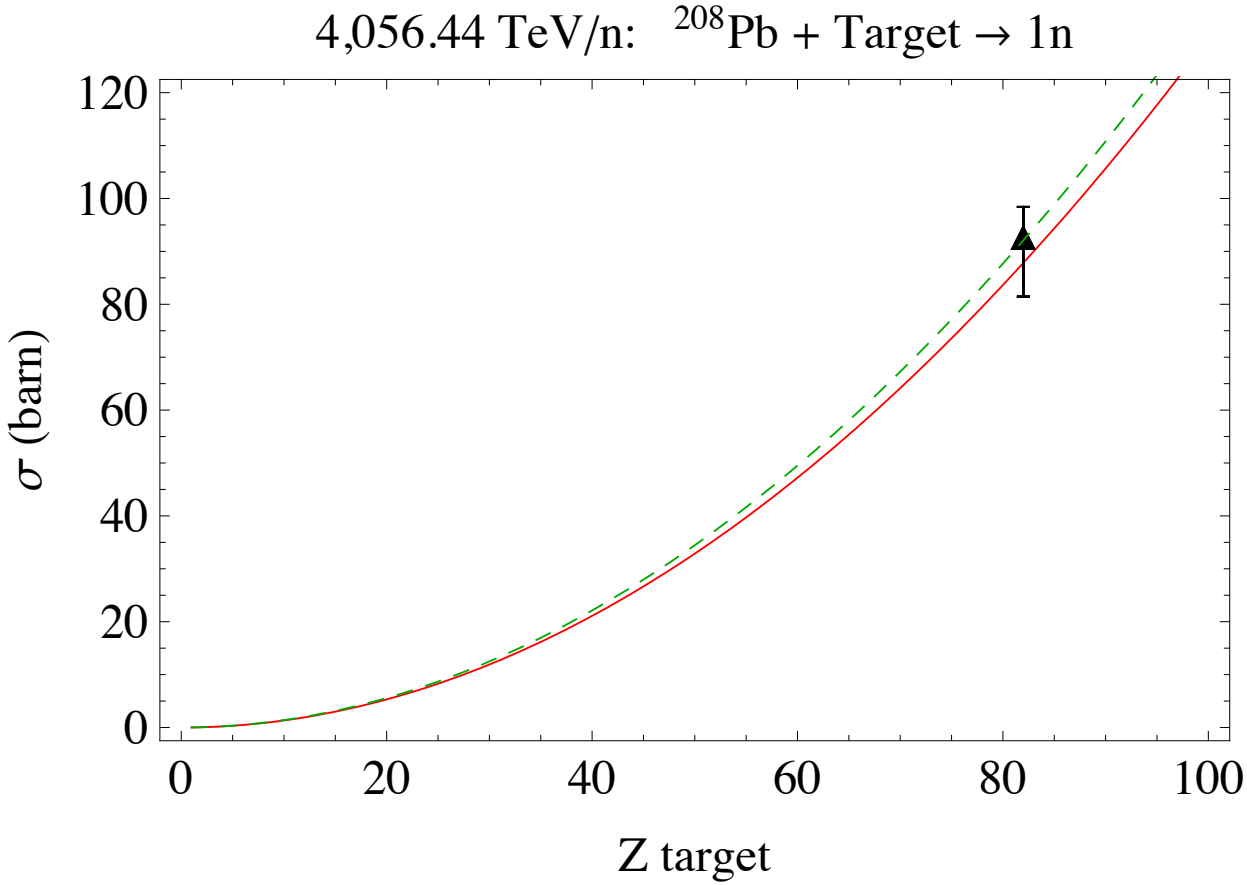






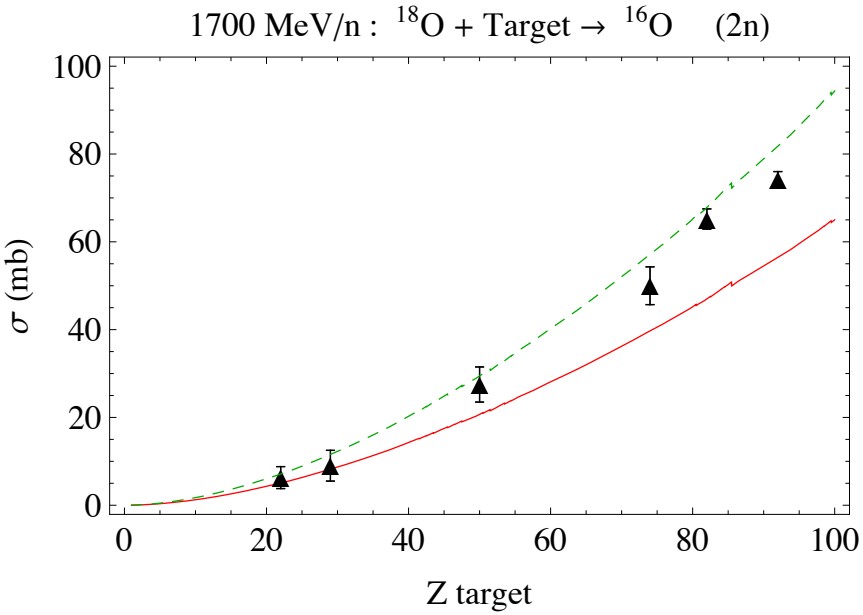
Excellent agreement for EMDFRG ——

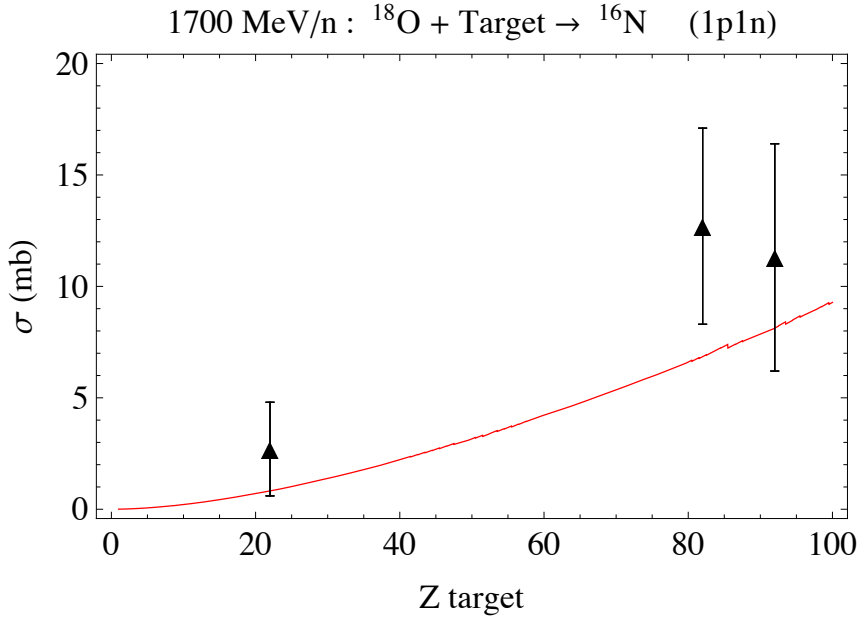
Large Hadron Collider (LHC)



Excellent agreement for EMDFRG ——

RESULTS - DOUBLE NUCLEON EMDFRG —– DATA - - -

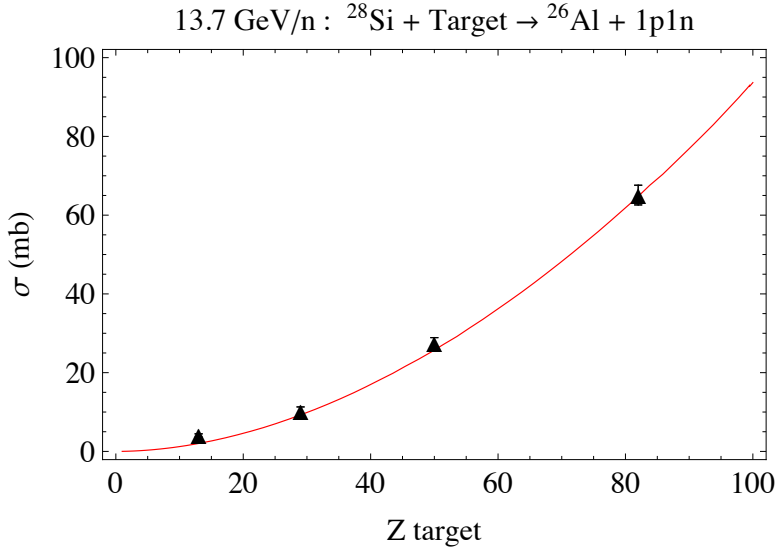




Good agreement for EMDFRG ——

$\sigma_{\mathrm{NUCFRG3}} = 0$

RESULTS - DOUBLE NUCLEON EMDFRG —– DATA - - - MMM



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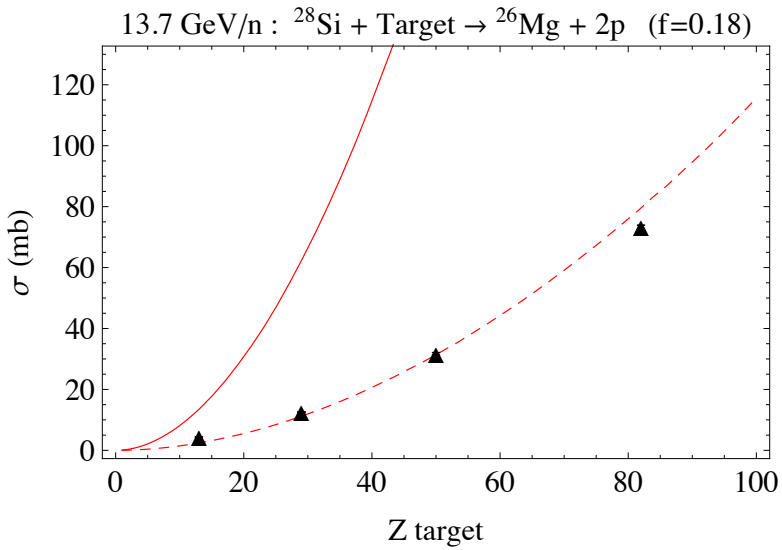
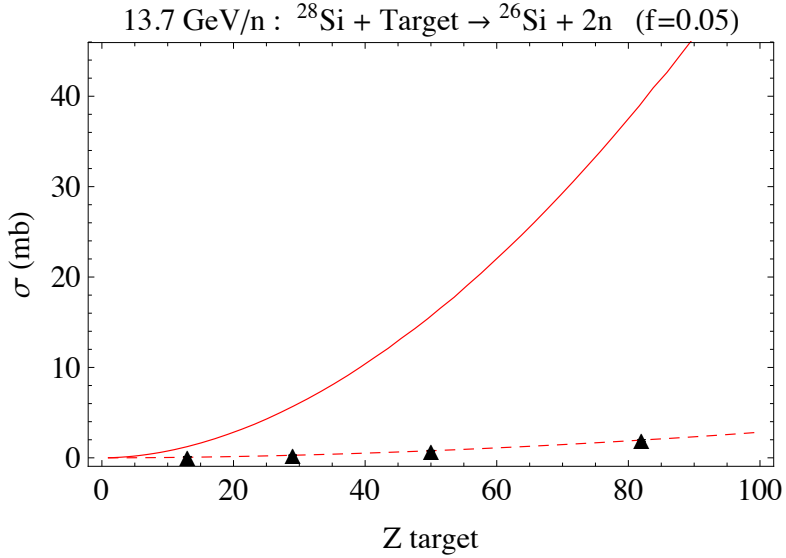
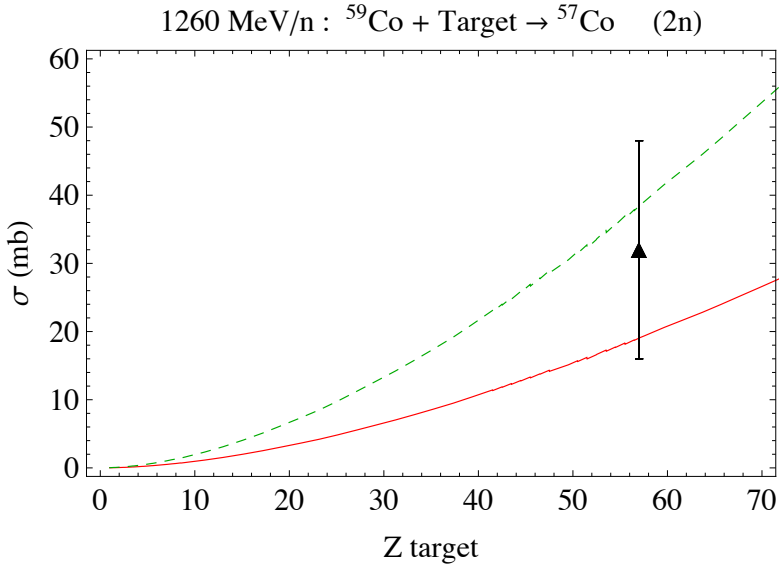
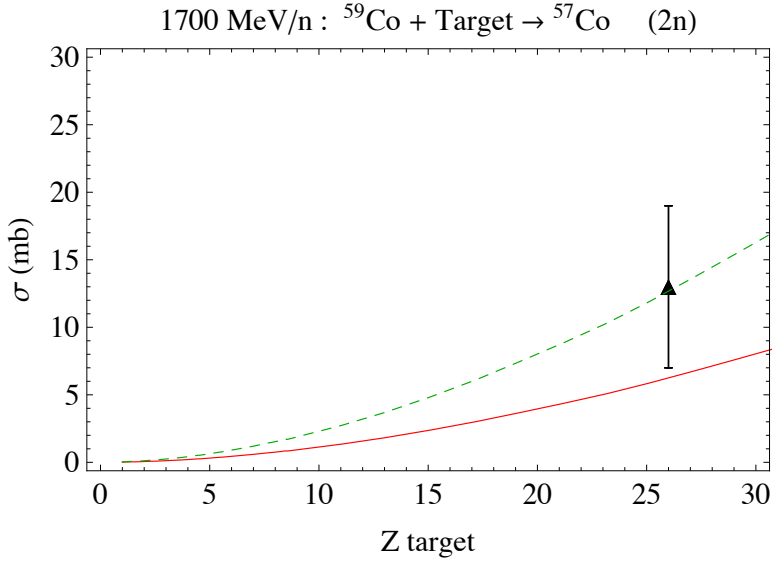


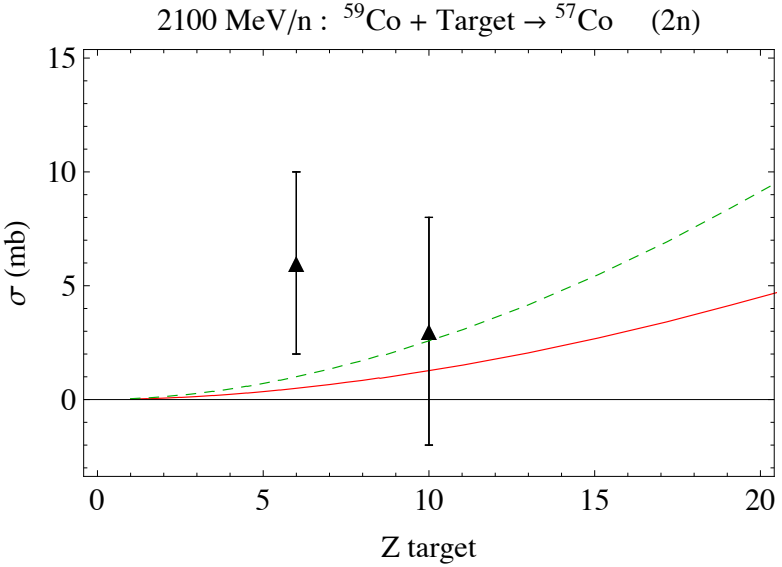


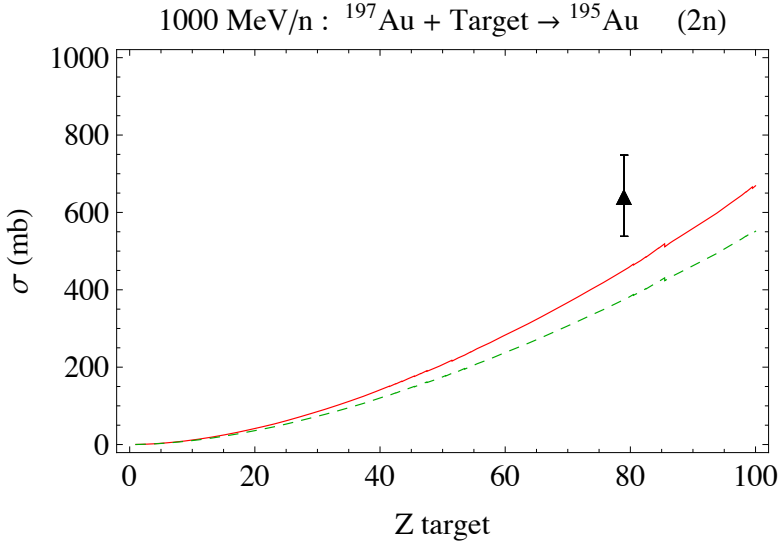
Poor agreement for EMDFRG ——— (fit = - - -) $\sigma_{\mathrm{NUCFRG3}} = 0$

RESULTS - DOUBLE NUCLEON EMDFRG —– DATA - - -





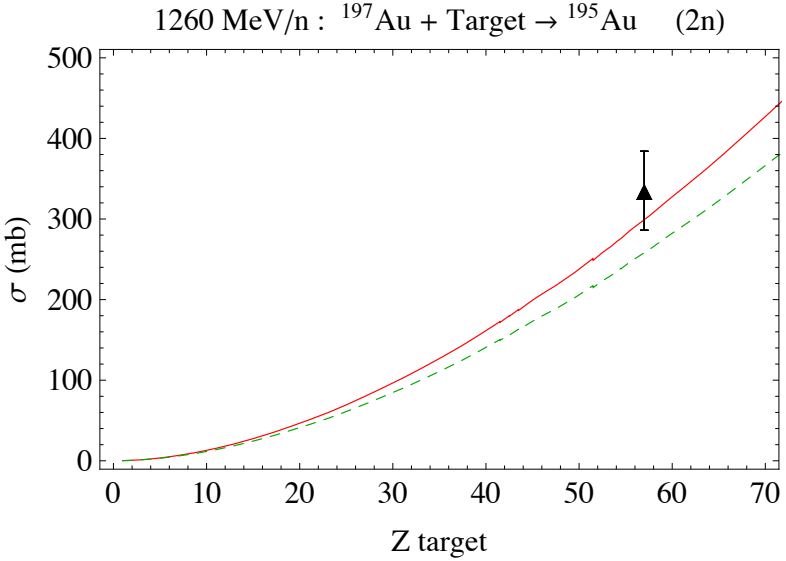


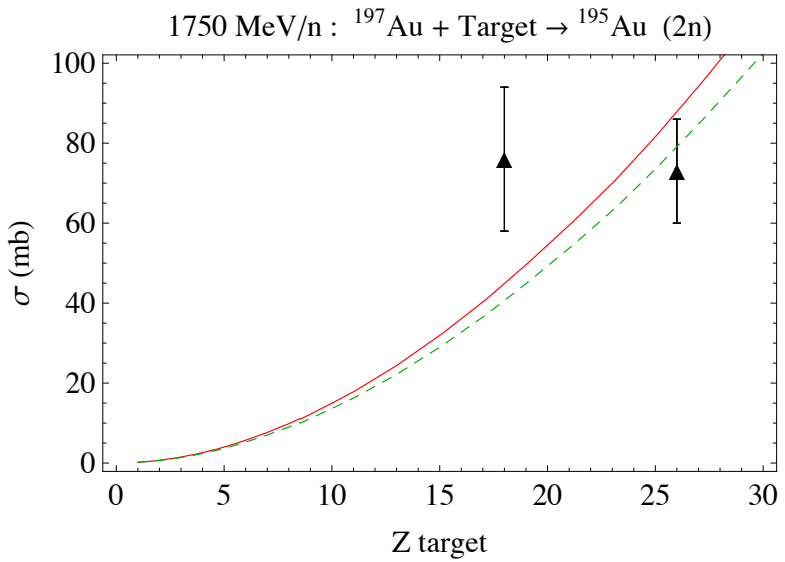


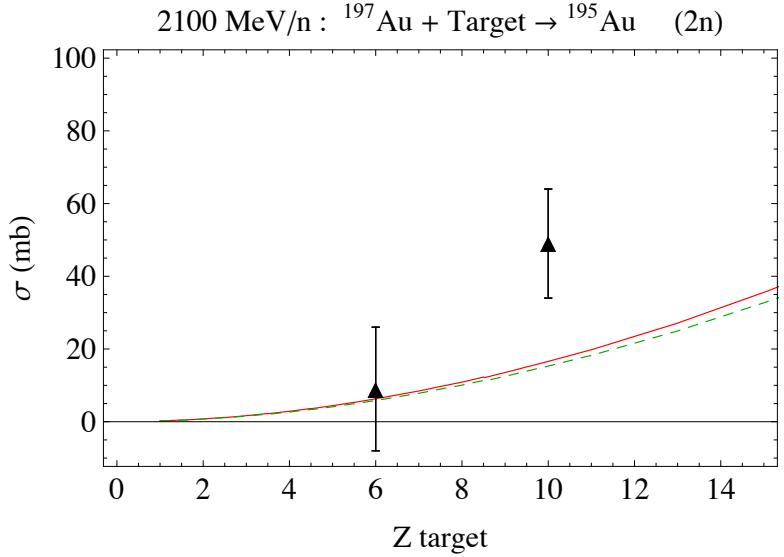
Good agreement for EMDFRG ——

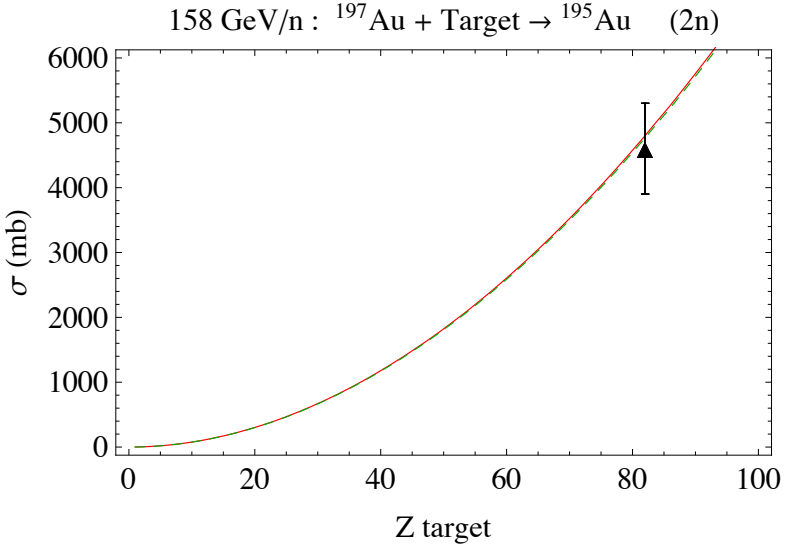
$\sigma_{\mathrm{NUCFRG3}} = 0$

RESULTS - DOUBLE NUCLEON EMDFRG —– DATA - - -





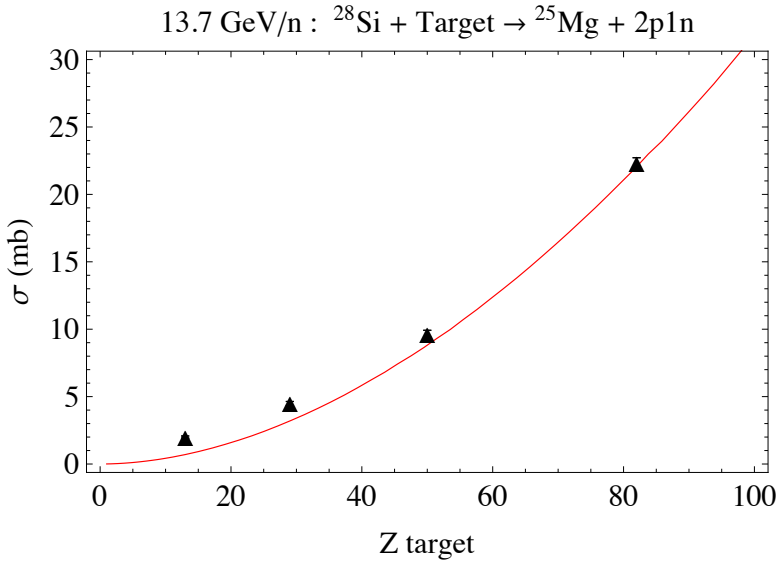


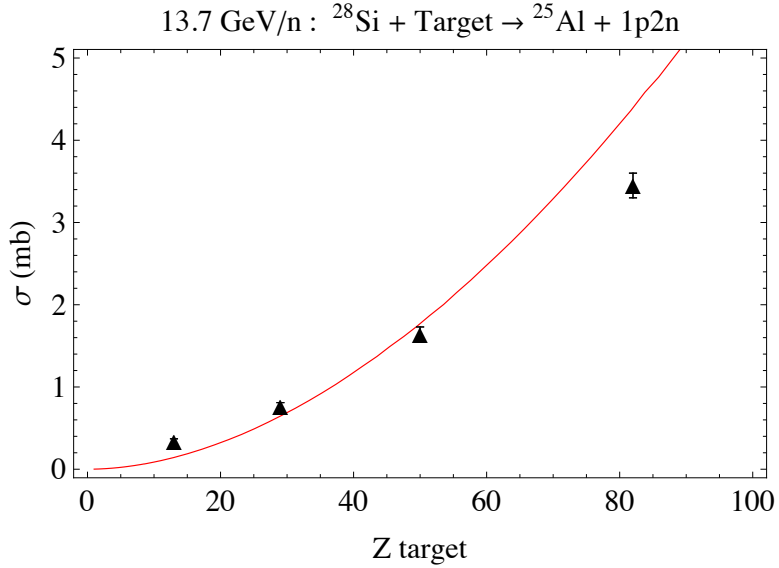


Reasonable agreement for EMDFRG ——

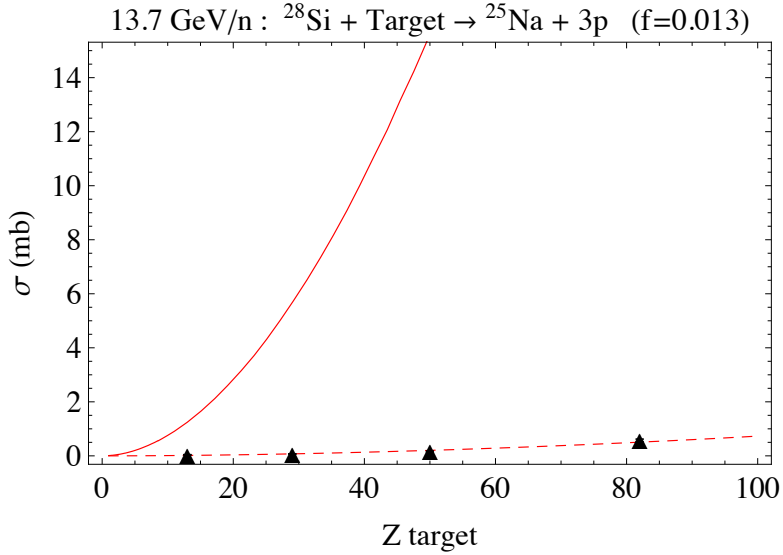
$\sigma_{\mathrm{NUCFRG3}} = 0$

RESULTS - TRIPLE NUCLEON



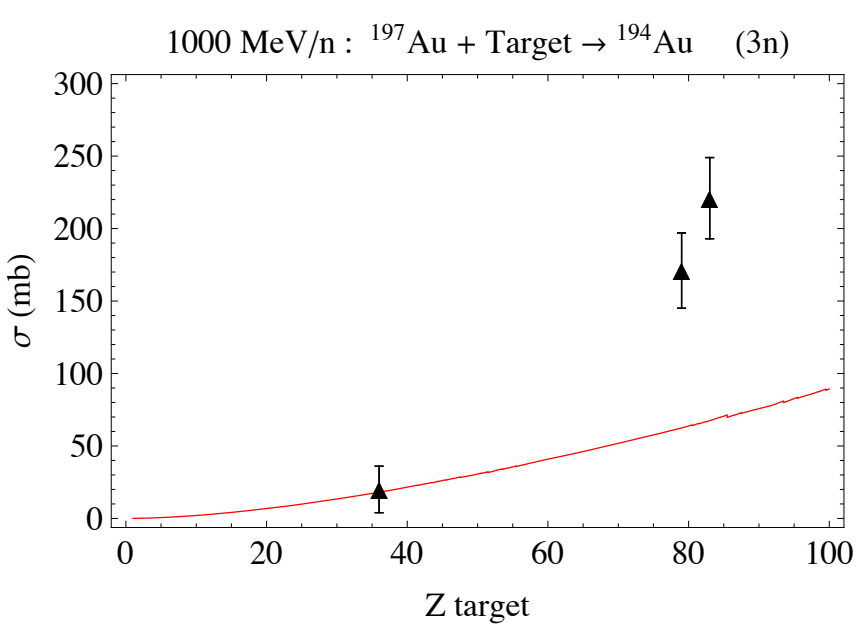


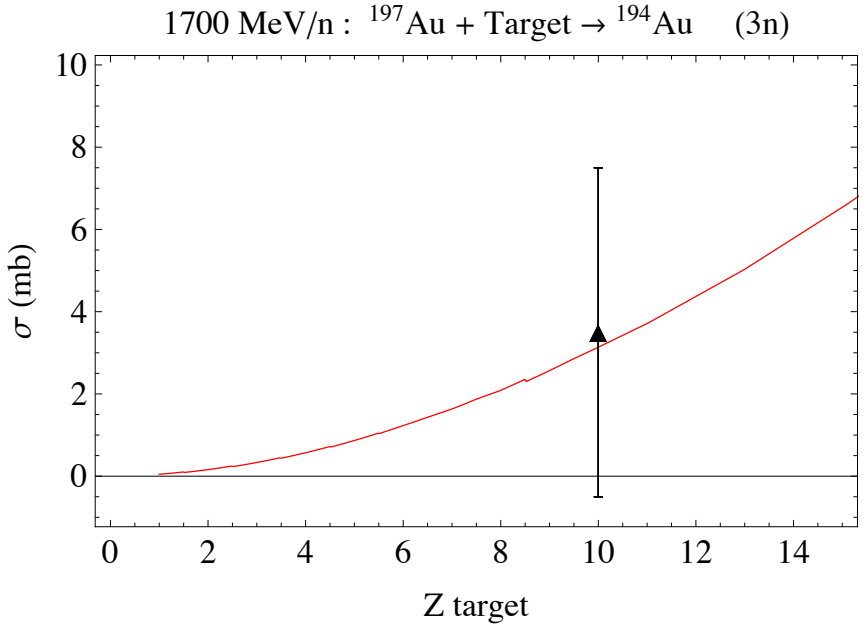
Excellent agreement for EMDFRG ——— $\sigma_{\mathrm{NUCFRG3}} = 0$



Poor agreement for EMDFRG ——— (fit = - - -) $\sigma_{\mathrm{NUCFRG3}} = 0$

RESULTS - TRIPLE NUCLEON

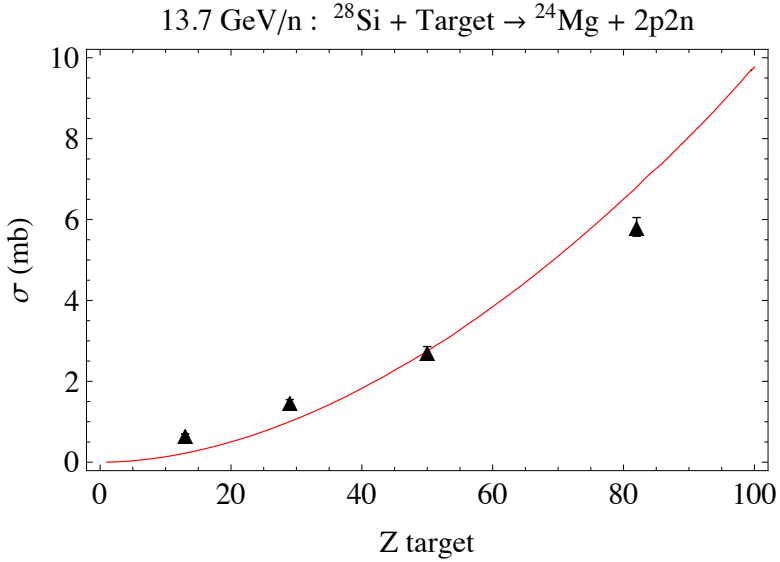


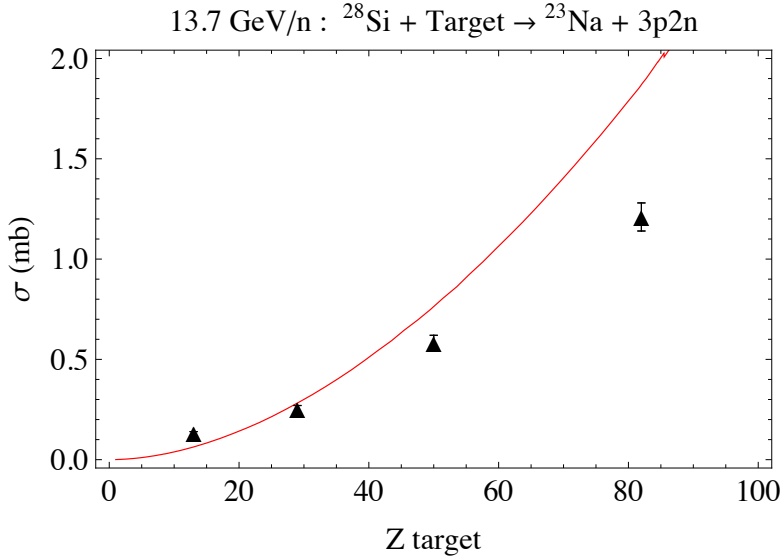


Mixed agreement for EMDFRG ——

$\sigma_{\text{NUCFRG3}} = 0$

Results - Many Nucleon





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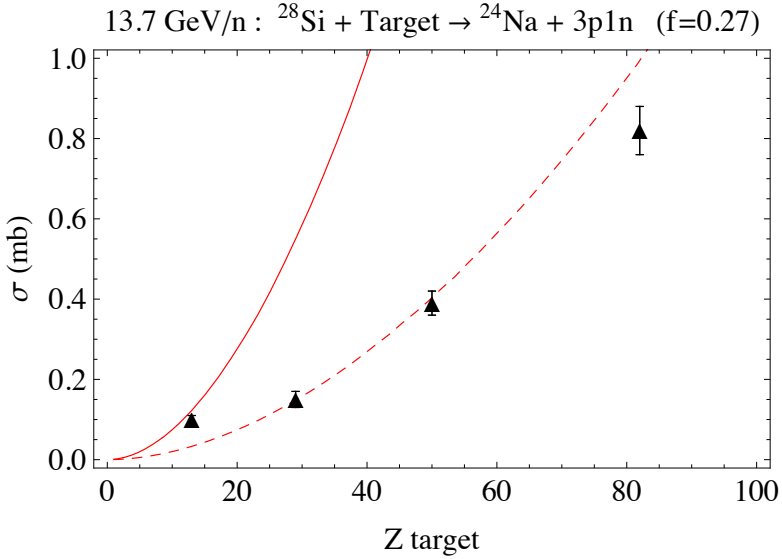
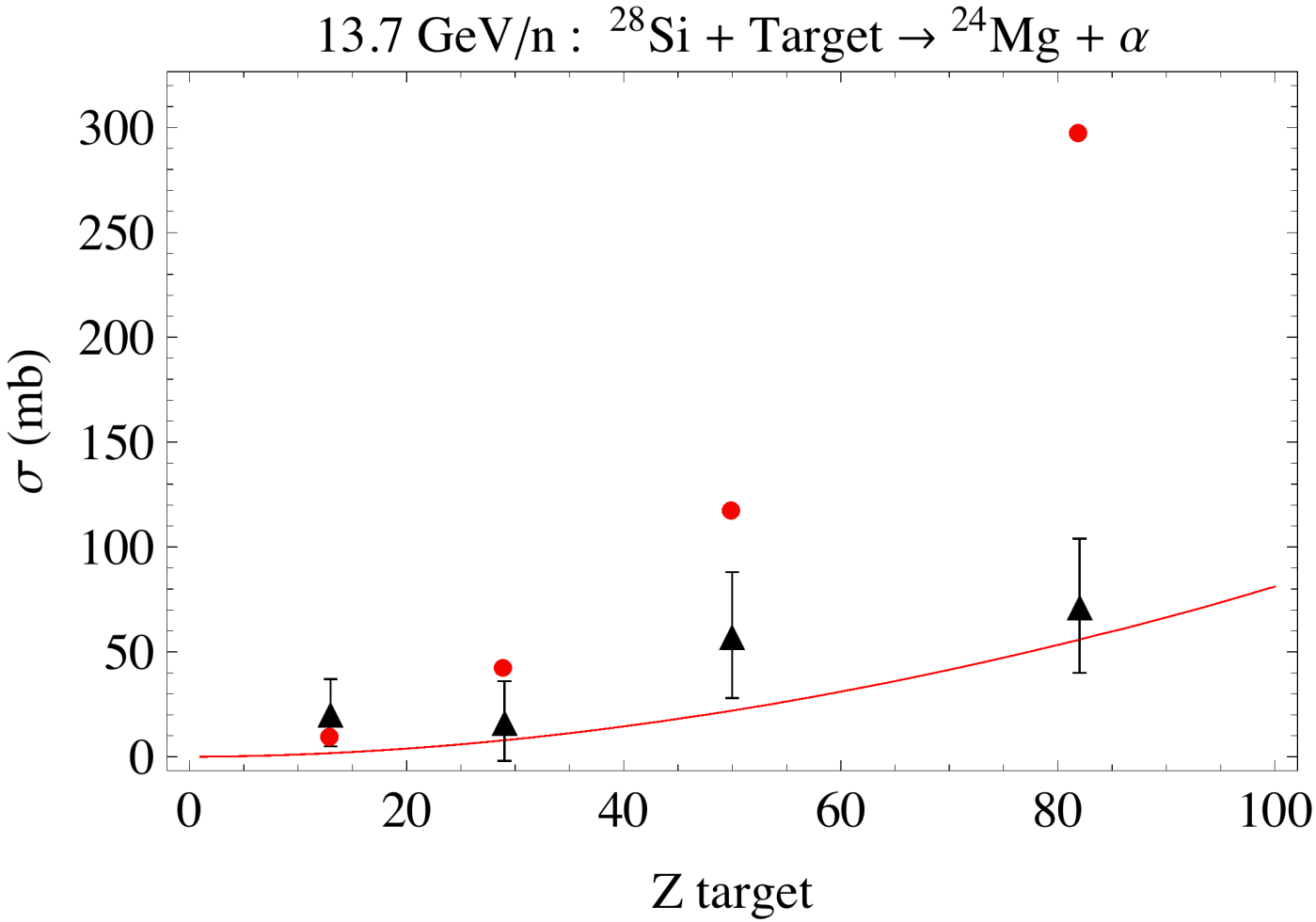


Poor agreement for EMDFRG ——— (fit = - - -) $\sigma_{\mathrm{NUCFRG3}} = 0$

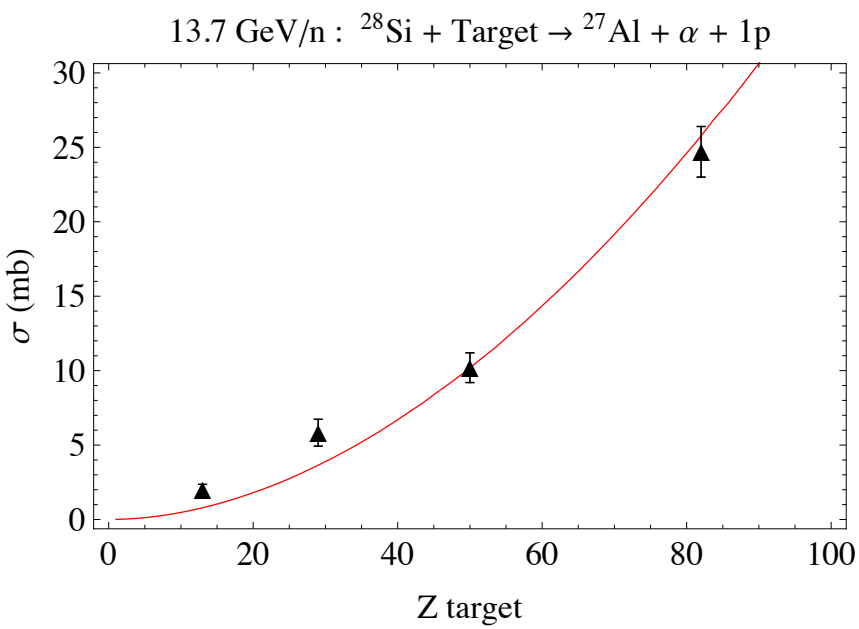
RESULTS - ALPHA

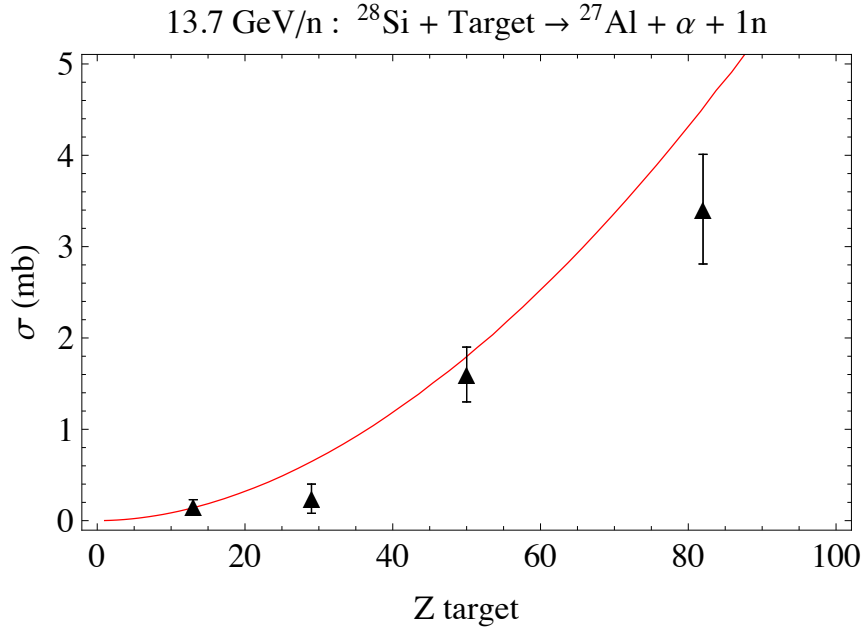
(ANOTHER REASON FOR DEVELOPING EMDFRG)



Excellent agreement for EMDFRG —— Poor agreement for NUCFRG3 • • • • •

Results - Alpha & Multiple N





Excellent agreement for EMDFRG —— $\sigma_{\mathrm{NUCFRG3}} = 0$

Conclusions

- New EMDFRG model for single & multiple nucleon & light ion
- Calculations are compared to *complete* set of experimental data
- Agreement with data is excellent for all cases relevant for space radiation
- Single, double & triple nucleon removal data agrees very well over the whole range of energies, projectiles and targets
- Alpha production data agrees very well for $^{28}\mathrm{Si}$ projectiles, including alpha production in coincidence with single nucleons
- Some discrepancies, but not important for space radiation, because cross sections are quite small
  - Exception is for double nucleon removal from $^{28}\mathrm{Si}$

THE END

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