Electromagnetic Dissociation Cross Sections for High LET Fragments

John Norbury
NASA Langley Research Center, Hampton, Virginia, USA

Wednesday February 10, 2016
2:15 - 2:30 pm (15 mins.)
INTRODUCTION

ELECTROMAGNETIC DISSOCIATION (EMD)

RESULTS

CONCLUSIONS
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: $^{56}\text{Fe} + \text{Al} \rightarrow ^{55}\text{Fe} + n + \text{Al}$
**Introduction: Strong vs. Electromagnetic (EM)**

\[ ^{56}\text{Fe} + ^{27}\text{Al} \rightarrow ^{55}\text{Fe} + \text{n} + ^{27}\text{Al} \]

Short range strong interaction when projectile & target nuclei overlap.

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**January 28, 2016**
Introduction: Strong vs. Electromagnetic (EM)

\[ ^{56}\text{Fe} + \text{Al} \rightarrow ^{55}\text{Fe} + \text{n} + \text{Al} \]

Short range strong interaction when projectile & target nuclei overlap.

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

\[ \sigma_{\text{EMD}} = \int dE_\gamma N(E_\gamma) \sigma(E_\gamma) \]

Photonuclear cross section \( \sigma(E_\gamma) \) shown by red curve, plotted against photon energy \( E_\gamma \). Green & blue curves show virtual photon spectra \( N(E_\gamma) \) for low & high energy projectiles.

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

New model EMDFRG accounts for multiple nucleon production
- 2p, 2n, 1p1n, 2p1n, 3p1\(\alpha\), 2p2t, ... (in addition to single light ions)

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

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

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

NUCFRG2 - - - - -

NUCFRG3 .........

Focus on EMDFRG ———— and NUCFRG3 .........
Excellent agreement for EMDFRG —— Poor agreement for NUCFRG3 ● ● ● ●
Results - Single Nucleon

EMDFRG —— Data — NUCFRG2 —— NUCFRG3

Excellent agreement for EMDFRG —— Worse agreement for NUCFRG3

2100 MeV/n: $^{16}O + \text{Target} \rightarrow ^{15}N$ (1p)

13.7 GeV/n: $^{28}Si + \text{Target} \rightarrow ^{27}Al + 1p$

2100 MeV/n: $^{16}O + \text{Target} \rightarrow ^{15}O$ (1n)

13.7 GeV/n: $^{28}Si + \text{Target} \rightarrow ^{27}Si + 1n$

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Similar agreement for EMDFRG —— and NUCFRG3 ● ● ● ●
RESULTS - SINGLE NUCLEON

- Good agreement for EMDFRG
- Poor agreement for NUCFRG3
Similar agreement for EMDFRG —— and NUCFRG3

1000 MeV/n : $^{197}$Au + Target $\rightarrow$ $^{196}$Au (1n)

1260 MeV/n : $^{197}$Au + Target $\rightarrow$ $^{196}$Au (1n)

1700 MeV/n : $^{197}$Au + Target $\rightarrow$ $^{196}$Au (1n)

2100 MeV/n : $^{197}$Au + Target $\rightarrow$ $^{196}$Au (1n)
Excellent agreement for EMDFRG ——
Results - Single Nucleon

Large Hadron Collider (LHC)

$4.05644 \text{ TeV/n: } ^{208}\text{Pb} + \text{Target} \rightarrow 1\text{n}$

Excellent agreement for EMDFRG ——–
Good agreement for EMDFRG

σ_{NUCFRG3} = 0
RESULTS - DOUBLE NUCLEON

EMDFRG —— DATA —— MMM

13.7 GeV/n: $^{28}\text{Si} + \text{Target} \rightarrow ^{26}\text{Al} + 1\text{p1n}$

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

13.7 GeV/n: $^{28}\text{Si} + \text{Target} \rightarrow ^{26}\text{Mg} + 2\text{p}$ (f=0.18)

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

13.7 GeV/n: $^{28}\text{Si} + \text{Target} \rightarrow ^{26}\text{Si} + 2\text{n}$ (f=0.05)
**RESULTS - DOUBLE NUCLEON**

EMDFRG --- DATA ---

1260 MeV/n : $^{59}\text{Co} + \text{Target} \rightarrow ^{57}\text{Co}$ (2n)

1700 MeV/n : $^{59}\text{Co} + \text{Target} \rightarrow ^{57}\text{Co}$ (2n)

2100 MeV/n : $^{59}\text{Co} + \text{Target} \rightarrow ^{57}\text{Co}$ (2n)

1000 MeV/n : $^{197}\text{Au} + \text{Target} \rightarrow ^{195}\text{Au}$ (2n)

Good agreement for EMDFRG

$\sigma_{\text{NUCFRG3}} = 0$
RESULTS - DOUBLE NUCLEON

Reasonable agreement for **EMDFRG** ——– σ_{NUCFRG3} = 0
RESULTS - TRIPLE NUCLEON

13.7 GeV/n: $^{28}\text{Si} + \text{Target} \rightarrow ^{25}\text{Mg} + 2p1n$

13.7 GeV/n: $^{28}\text{Si} + \text{Target} \rightarrow ^{25}\text{Al} + 1p2n$

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

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

13.7 GeV/n: $^{28}\text{Si} + \text{Target} \rightarrow ^{25}\text{Na} + 3p$ (f=0.013)

RESULTS - TRIPLE NUCLEON

Mixed agreement for EMDFRG

\[ \sigma_{\text{NUCFRG3}} = 0 \]
**RESULTS - MANY NUCLEON**

13.7 GeV/n: $^{28}$Si + Target $\rightarrow ^{24}$Mg + 2p2n

13.7 GeV/n: $^{28}$Si + Target $\rightarrow ^{23}$Na + 3p2n

Good agreement for EMDFRG

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

Poor agreement for EMDFRG (fit = - - -)

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

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RESULTS - ALPHA

(ANOTHER REASON FOR DEVELOPING EMDFRG)

Excellent agreement for EMDFRG

Poor agreement for NUCFRG3

13.7 GeV/n: $^{28}\text{Si} + \text{Target} \rightarrow ^{24}\text{Mg} + \alpha$

Excellent agreement for EMDFRG  Poor agreement for NUCFRG3
Excellent agreement for EMDFRG ——– $\sigma_{\text{NUCFRG3}} = 0$
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 $^{28}\text{Si}$ 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 $^{28}\text{Si}$
THE END

john.w.norbury@nasa.gov