Nuclear Cross Sections for Space Radiation Applications

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Outline

- Space Radiation Environment
- Lippmann-Schwinger Equation
- Interaction and Parameterizations
- Models
- Results
- Conclusions
INTRODUCTION

- Space Radiation Environment
  - Galactic Cosmic Rays
  - Solar Particle Events

- Accurate cross sections are needed for radiation transport

Hubble Space Telescope
Solar Dynamics Observatory
Lippmann-Schwinger Equation:

- Lippmann-Schwinger Equation: \( T = V + VG_0^+T \)
- For elastic scattering, use equivalent set of coupled equations
  - Elastic Scattering Equation:
    \[
    T = U + UPG_0^+PT
    \]
- Optical Potential:
  \[
  U = V + VQG_0^+QU
  \]
- Elastic scattering equation in momentum-space
  \[
  T(k', k) = U(k', k) + \int U(k', k'')G_0^+(k'', k)T(k'', k)dk''
  \]
  where
  \[
  G_0^+(k'', k) = \frac{1}{E(k) - E(k'') + i\eta}
  \]
Interaction

- Potential is sum of nucleon-nucleon (NN) interactions

\[ V = \sum_{i=1}^{A_P} \sum_{j=1}^{A_T} v_{ij} \]

- Write series in terms of pseudo two-body operators

\[ U_{ij} = \tau_{ij} + \tau_{ij} QG_0^+ Q \sum_{lm} U_{lm} \]

where

\[ \tau_{ij} = v_{ij} + v_{ij} QG_0^+ Q \tau_{ij} \]

- Express \( \tau_{ij} \) in terms of \( t_{ij} \)

\[ \tau_{ij} = t_{ij} + t_{ij} (QG_0^+ Q - g) \tau_{ij} \]
Impulse approximation: $\tau_{ij} \rightarrow t_{ij}$

- Single Scattering
- Optimum Factorization
- Transition amplitude evaluated at beam energy for central potentials

\[
U(k', k) = A_PA_T\eta t_{NN}(q, \epsilon)\rho_T(q)\rho_P(q)
\]
PARAMETERIZATIONS

- **Nuclear Matter Density**
  - For $A \leq 16$, Harmonic-Well Model\(^1\)
  - For $A > 16$, Two parameter Fermi Model\(^1\)
  - If no data for $A \leq 16$, isotopic average of parameters is used
  - If no data for $A > 16$, Nuclear Droplet Model\(^2\) is used

- **NN transition amplitude\(^3\)**
  - Cross sections
  - Real to imaginary ratio
  - Slope parameters

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\(^3\) Werneth et al. NASA Technical Publication 2014-218529
MODELS

- **Eikonal (Eik)**
  - High Energy, Forward Scattering
  - Non-relativistic

- **Partial Wave (PW)**
  - Relativistic kinematics easily incorporated
  - Partial wave decomposition is an approximation
  - Numerically unstable for large number of partial wave
  - Finite summation formulas were implemented\(^4\)

- **Three-Dimensional Lippmann-Schwinger\(^5\) (LS3D)**
  - Relativistic kinematics easily incorporated
  - Not an approximation
  - Extended to reactions relevant for space radiation applications\(^6\)

Unequal Mass Comparisons

$T_{\text{Lab}} = 1$ GeV/n ($p + ^{56}\text{Fe}$)

$T_{\text{Lab}} = 20$ GeV/n ($p + ^{16}\text{O}$)
Comparison to Experiment

Comparison to Experiment

\[ T_{\text{Lab}} = 1047 \, \text{MeV/nucl. (p +}^{58}\text{Ni)} \]

\[ N_{\text{Lab}} = 342 \, \text{MeV/nucl. (}^4\text{He +}^{40}\text{Ca)} \]

- Lombard et al.
- LS3D (NR)
- LS3D (REL)

REL kinematic effects depend on mass difference and lab energy

REL results agree better with experimental data than NR results

No REL effect observed for equal mass systems

Equal mass results can be explained with rapidly decaying potential