Heavy-Ion Transport in the MARS15 Code

Igor Rakhno

University of Illinois at Urbana-Champaign

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Introduction

The MARS Monte Carlo code is used in numerous accelerator and cosmic ray applications as well as for detector and shielding studies.

Recent needs:

- Relativistic Heavy-Ion Collider
- Large Hadron Collider
- Rare Isotope Accelerator
- NASA projects (Joint Dark Energy Mission/SNAP)

Heavy-ion interaction and transport physics has been recently incorporated into the MARS15 code. The key modules of the new implementation are described below along with their comparisons to experimental data: **event generators**, **nucleus-nucleus cross sections**, and **mean stopping power**. Benchmarking results for a macroscopic system are presented as well.

Heavy-Ion Event Generator

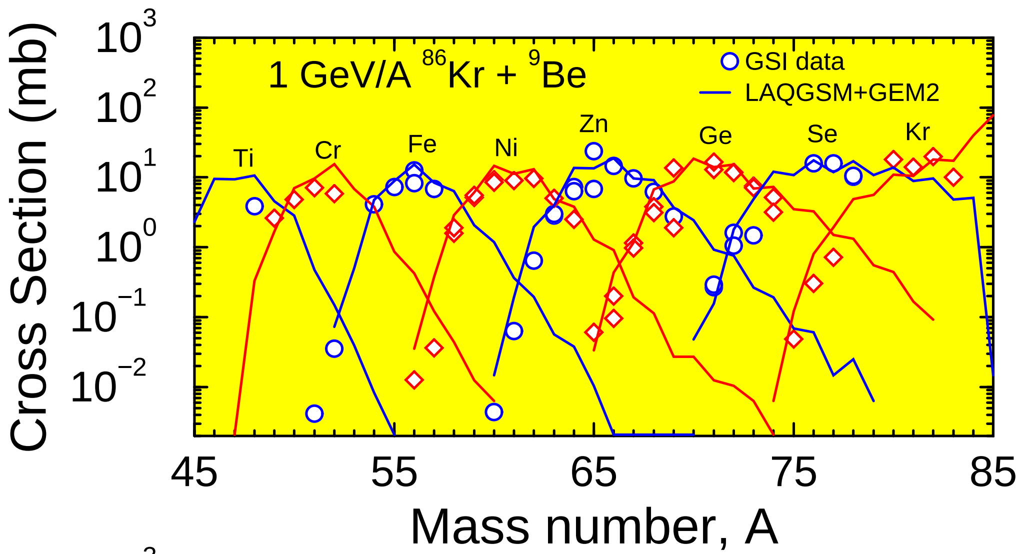
The 2003 version of the LAQGSM (*LANL, K. Gudima, S. Mashnik, A. Sierk*) code was implemented into MARS15 after substantial revisions and merging with CEM03 and native MARS14 modules. It can now be used in full transport simulations in complex macro-systems for modeling all heavy-ion and hadron nuclear interactions from 10 MeV/A to 800 GeV/A as well as photo-nuclear interactions.

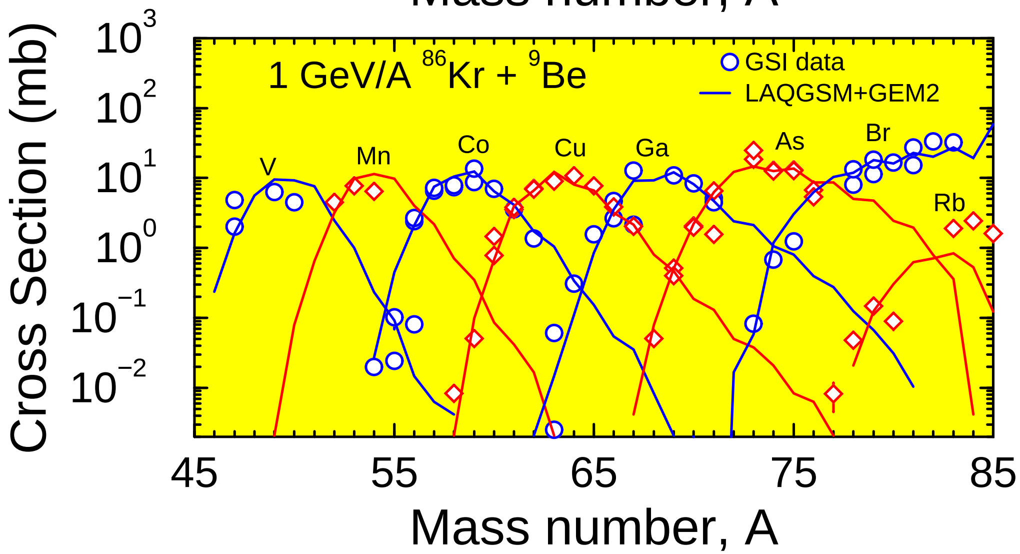
LAQGSM03 includes:

- improved version of the Dubna intra-nuclear cascade model that makes use of experimental elementary cross sections (or those calculated with the Quark-Gluon String Model for energies above 4.5 GeV/A);
- pre-equilibrium model from the improved Cascade-Exciton Model - CEM03 code;
- refined versions of the Fermi break-up and coalescence models, and an improved version of the Generalized Evaporation-fission Model (GEM2).

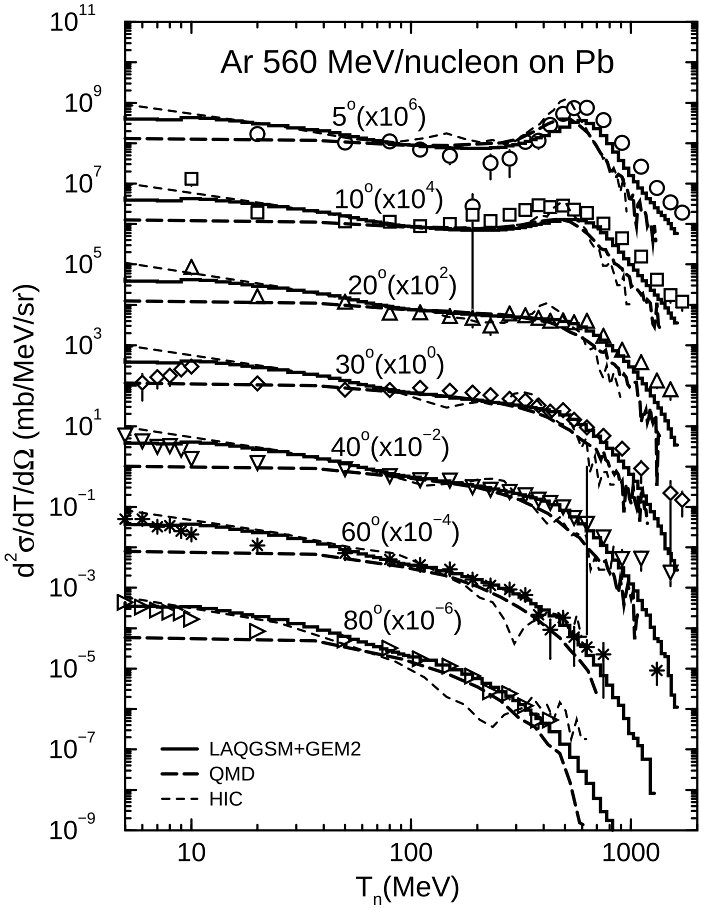
All this provides for consistent modeling of exclusive and inclusive distributions of secondary particles, spallation, fission, and fragmentation products.

Heavy-Ion Event Generator — Nuclide Production in MARS15 at 1 GeV/A





Heavy-Ion Event Generator — Neutron Differential Cross Sections



Nucleus-Nucleus Interaction Cross Sections in MARS15

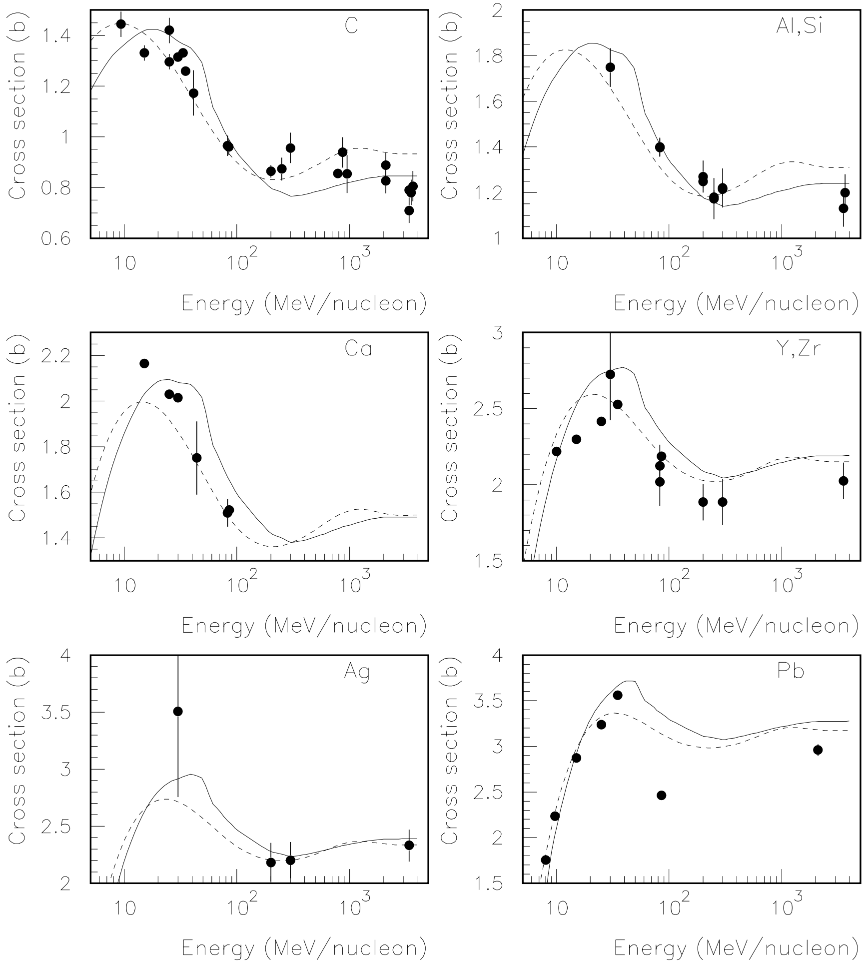
Inelastic and elastic cross sections for heavy ion nuclear interactions have been studied both theoretically and experimentally for the past several decades. Experimental data by different groups in many cases contradict each other.

Several empirical prescriptions have been developed for **inelastic** cross sections. Most recent and comprehensive studies were performed at NASA (*R.K. Tripathi et al*.) and JINR (*V.S. Barashenkov et al*.).

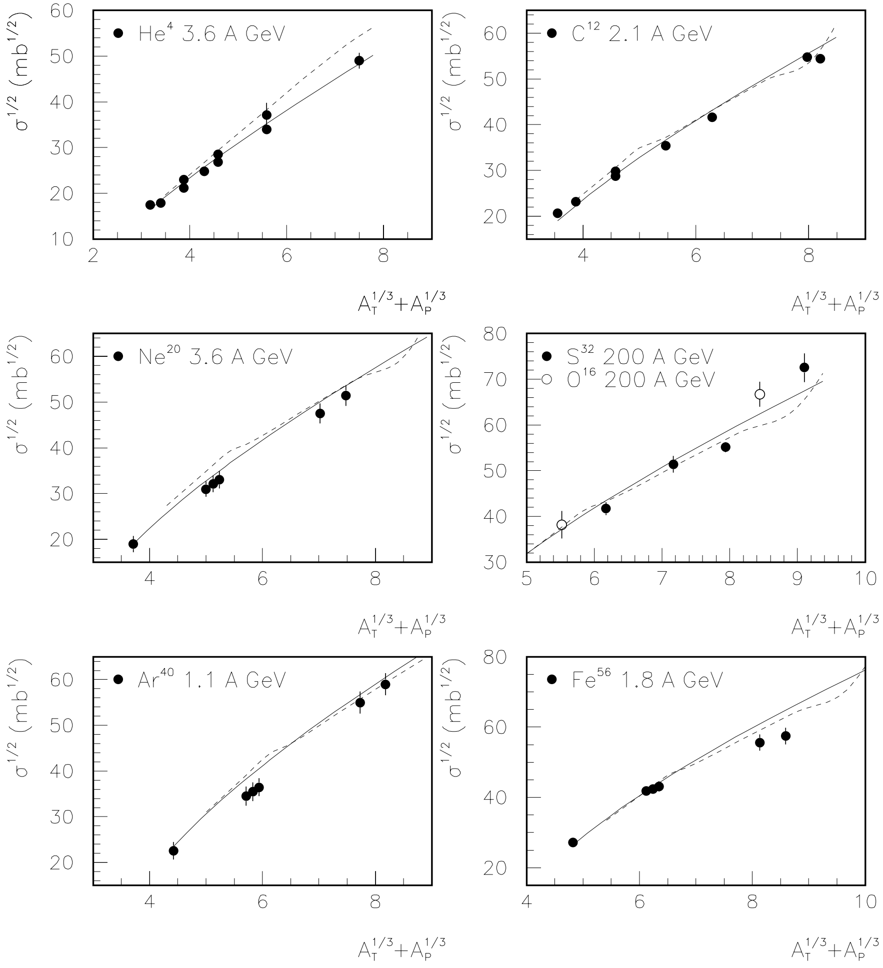
Both the models show reasonable agreement with experimental data for energy range from a few A MeV up to 200 A GeV and for ions, both projectiles and targets, ranging from deuteron to lead.

The JINR model was chosen as default one for MARS15 because it describes also **elastic** cross sections required for full particle transport.

Nucleus-Nucleus Interaction Cross Sections in MARS15



^{12}C−nucleus reaction cross section



Nucleus−nucleus reaction cross section

Mean Stopping Power (1)

The mean ionization energy loss, dE/dx, is calculated using the Bethe-Bloch formalism in combination with various corrections. Three additional corrections have been implemented into the code to describe better the **Barkas effect** (Z_1^3 terms) and take into account **electron capture** by low-energy ions.

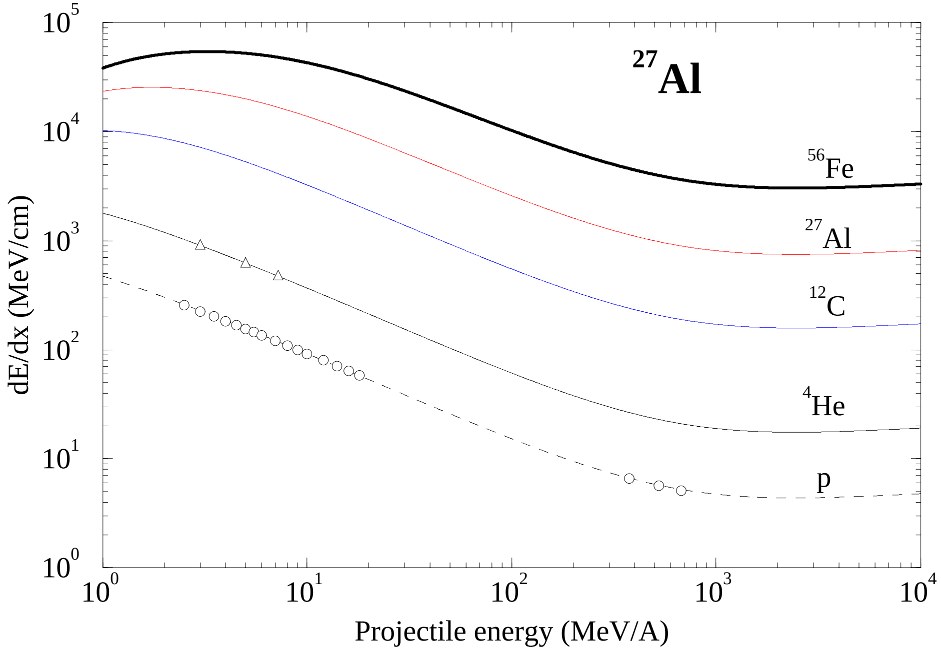
$$-\frac{dE}{dx} = \frac{Z_1^2 e^4 n_e}{4\pi\varepsilon_0^2 \, 2m_e v^2} L,$$

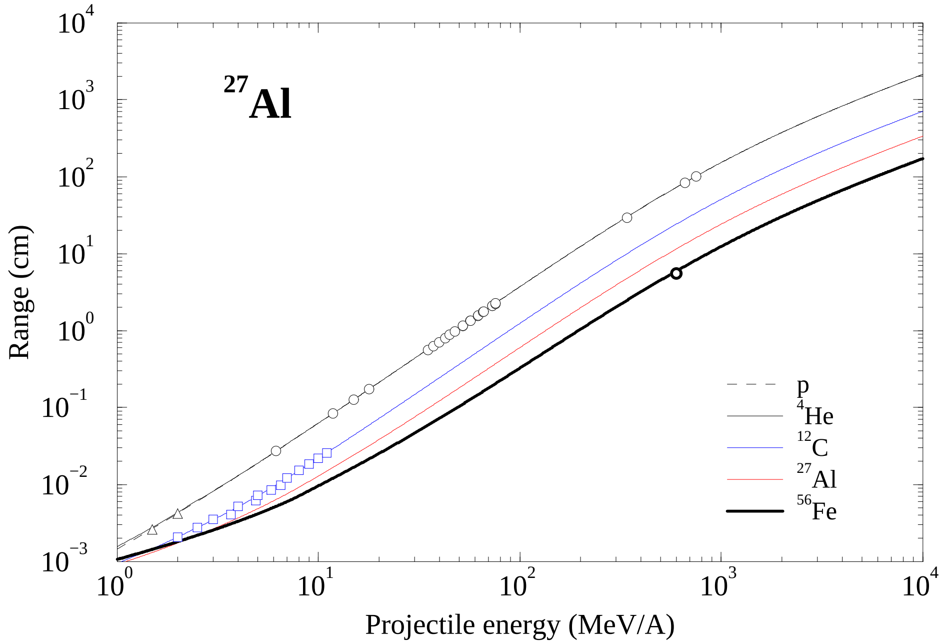
where

$$L = L_0 + \sum_i \Delta L_i \quad \text{and} \quad L_0 = \ln\left(\frac{2m_e c^2 \beta^2 \gamma^2}{I}\right) - \beta^2 - \frac{\delta}{2}$$

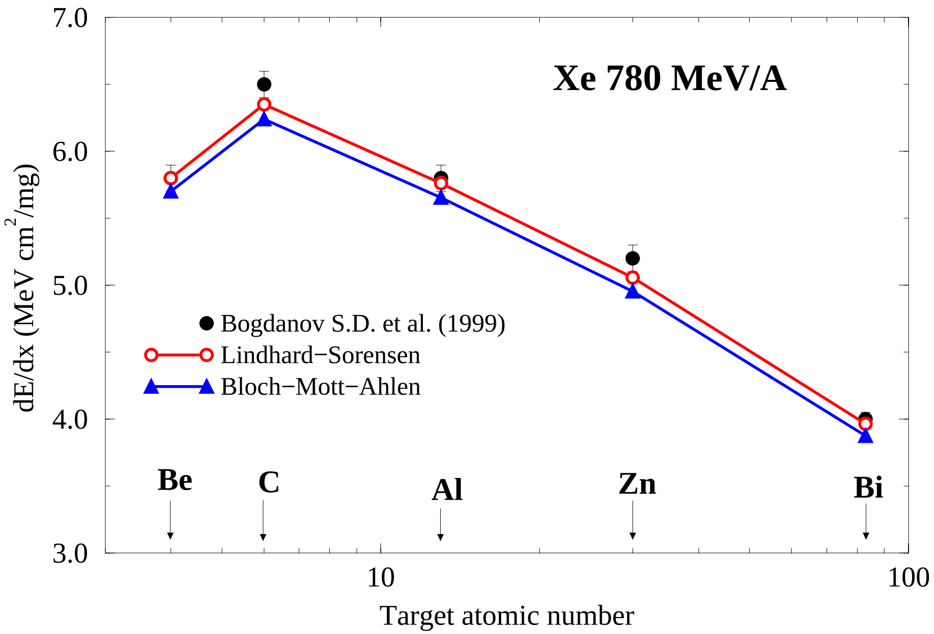
Electron capture reveals itself as a significant decrease in an ion charge at low kinetic energies. The so-called effective ion charge, Z_{eff}, is determined according to semi-empirical formulae and used instead of bare projectile charge.

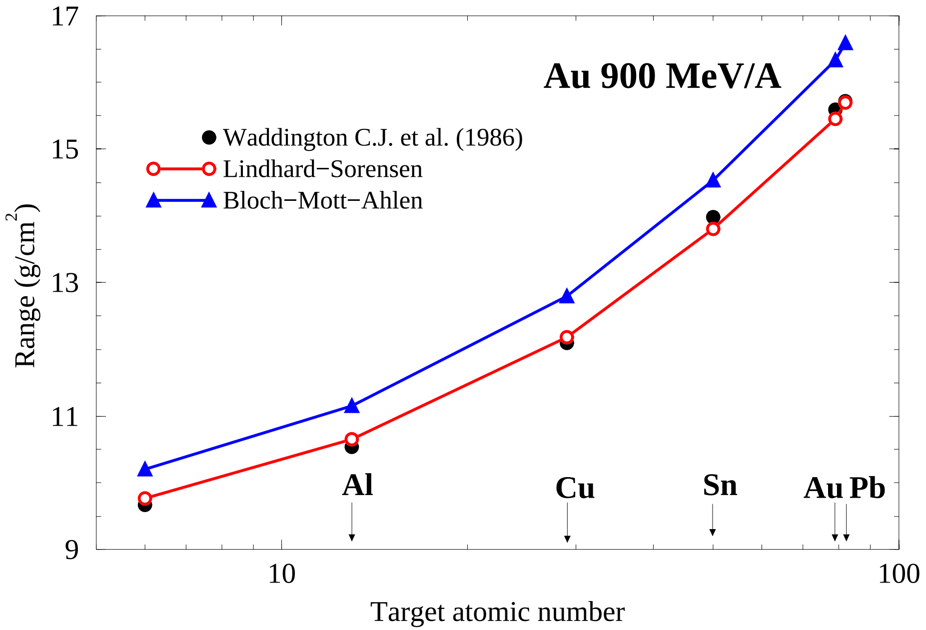
Mean Stopping Power (2)



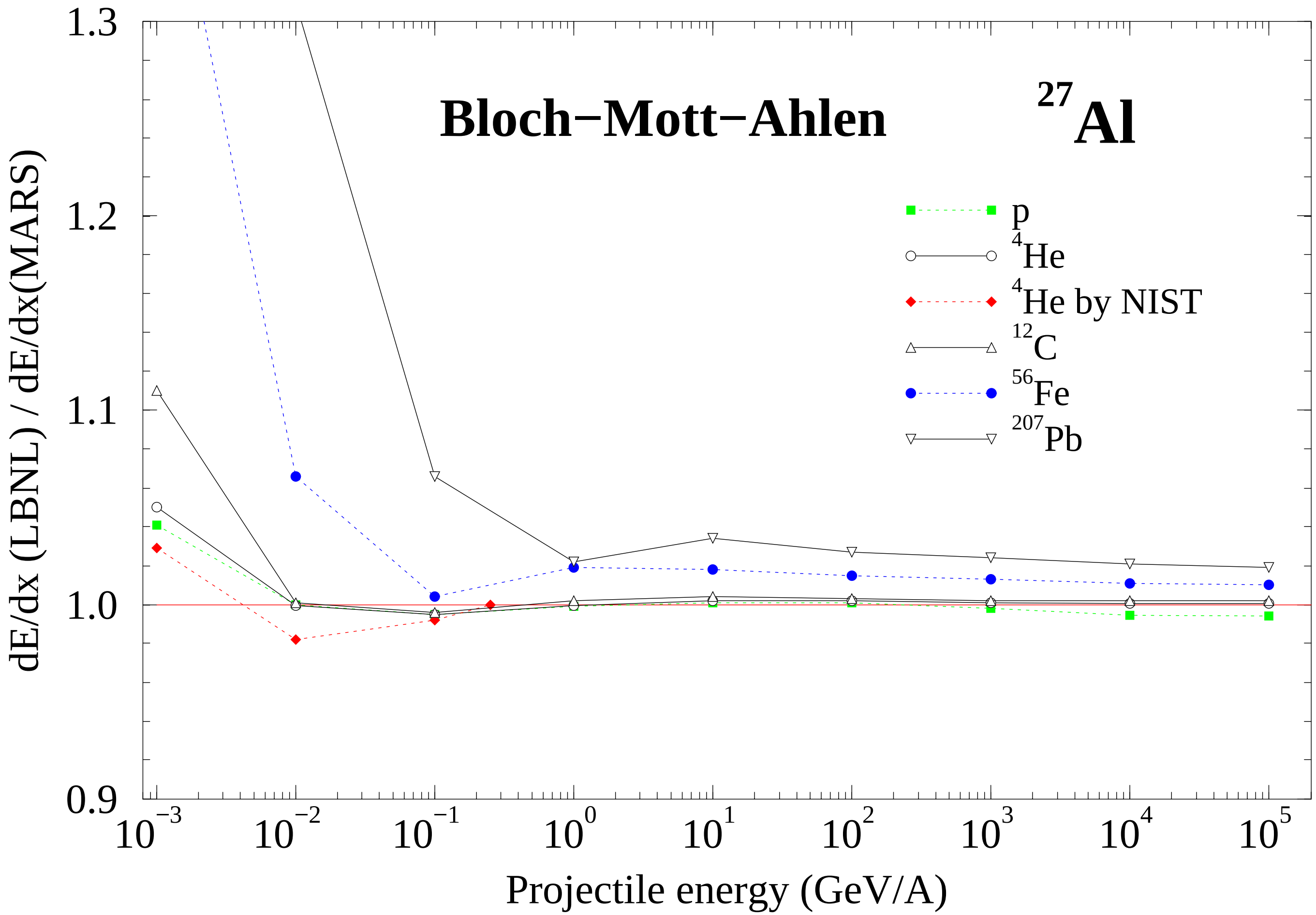


Mean Stopping Power (3)

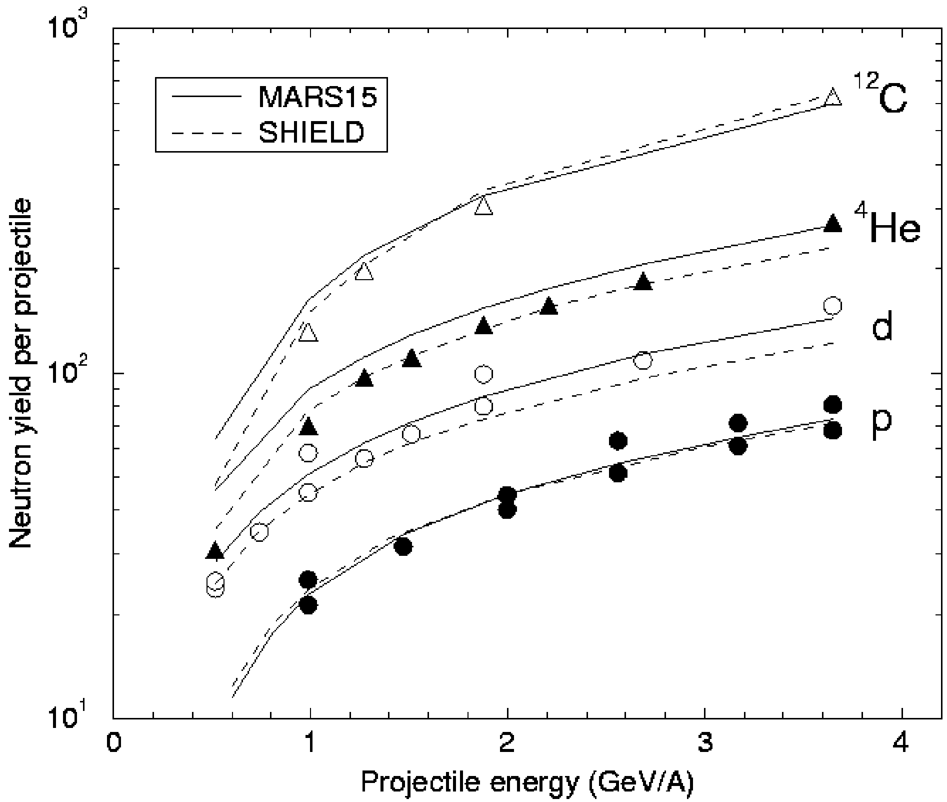




Mean Stopping Power (4)



Macroscopic Tests



Calculated and measured total neutron yield (T_n < 14.5 MeV) from a lead cylinder, 10 cm in radius and 60 cm in length, irradiated with light ion beams.

Conclusions

- **Heavy-ion interaction and transport physics has been implemented into MARS15 Monte Carlo code.**
- **First comparisons between theory and experiment for integral neutron yields reveal good results.**
- **Further development of this package is underway.**