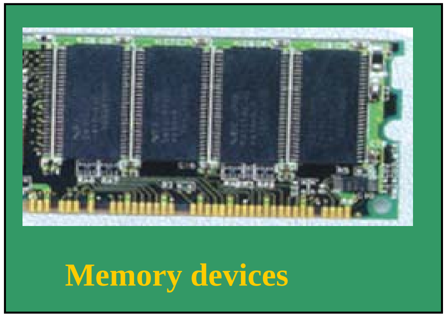
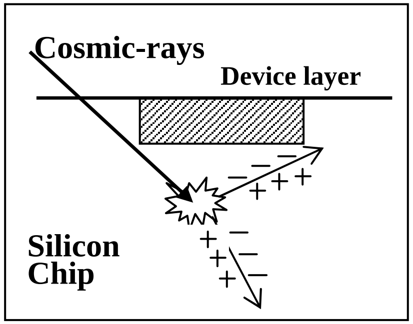
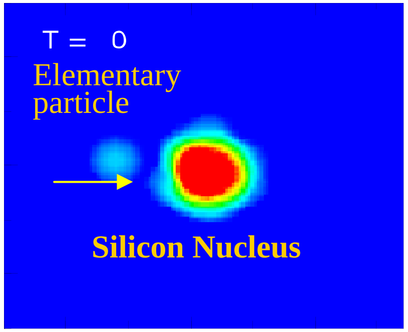
Presented at INPC2007, June 3-8, 2007, Tokyo, Japan

Cosmic-rays induced single-event upsets in microelectronics and related nuclear reaction database

- The role of nuclear physics in IT society -







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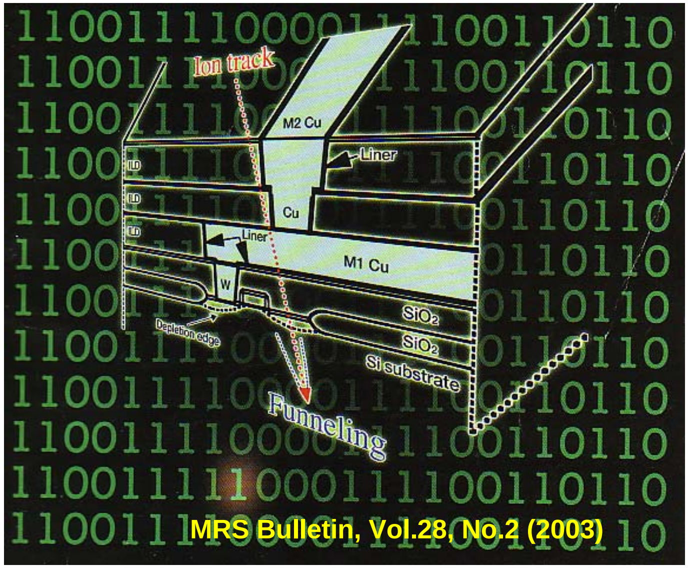
Outline

1. Introduction: Single-Event Upset (SEU)
2. Model for SEU simulation and nuclear data
3. Results and discussion
4. Summary and conclusions

Introduction

Single-Event Upset (SEU)

- **One of the radiation effects caused in microelectronic devices**
  (e.g., semiconductor memory devices) used in various cosmic-ray environments



- When a memory device is exposed to radiations, **the memory state of a cell can be flipped from a 1 to a 0 or vice versa**, resulting in malfunction caused by an error in a bit.

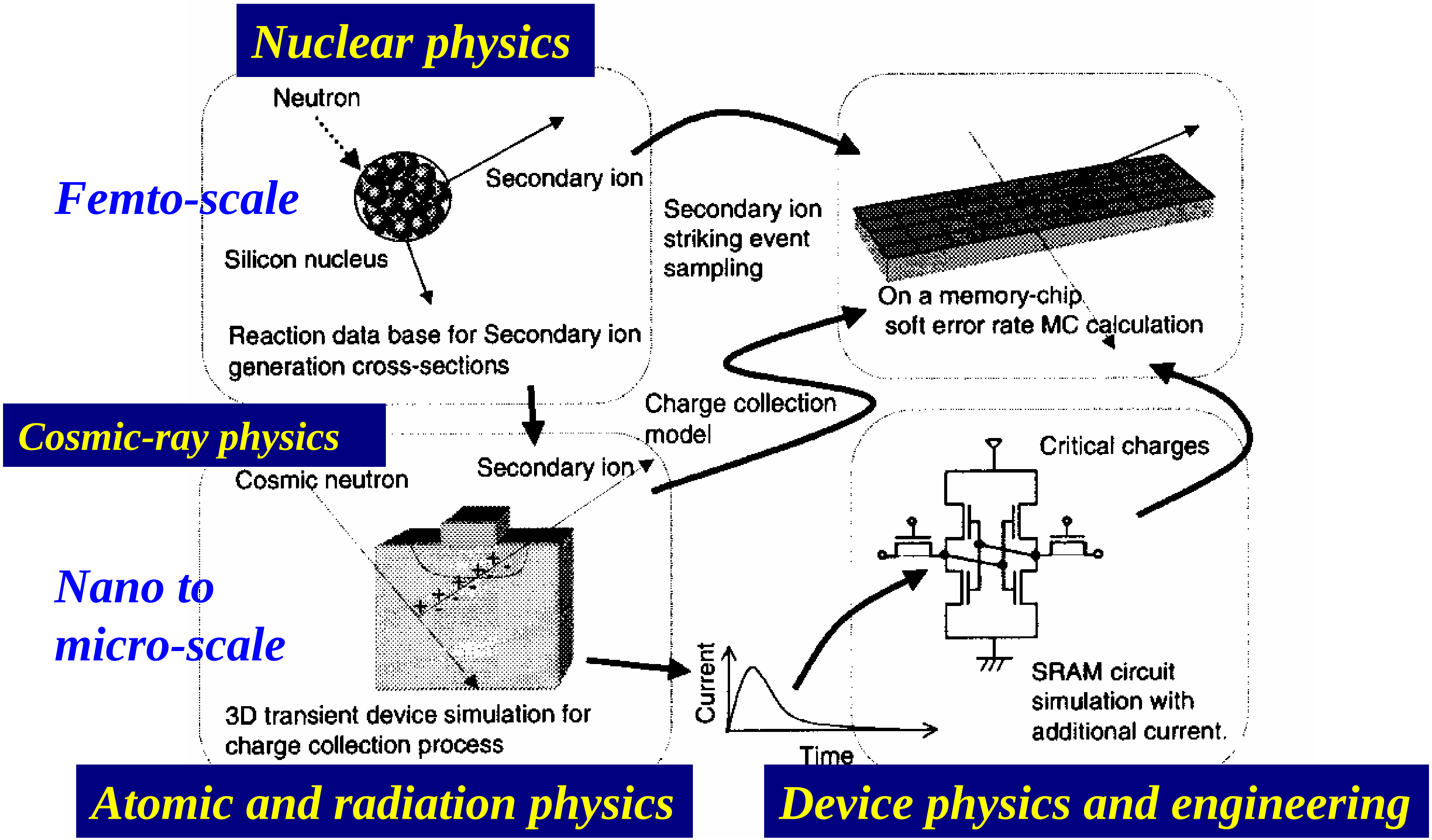
- **“Transient" effect** caused by a single ionizing particle

⇨ **Soft Error or Soft Failure**

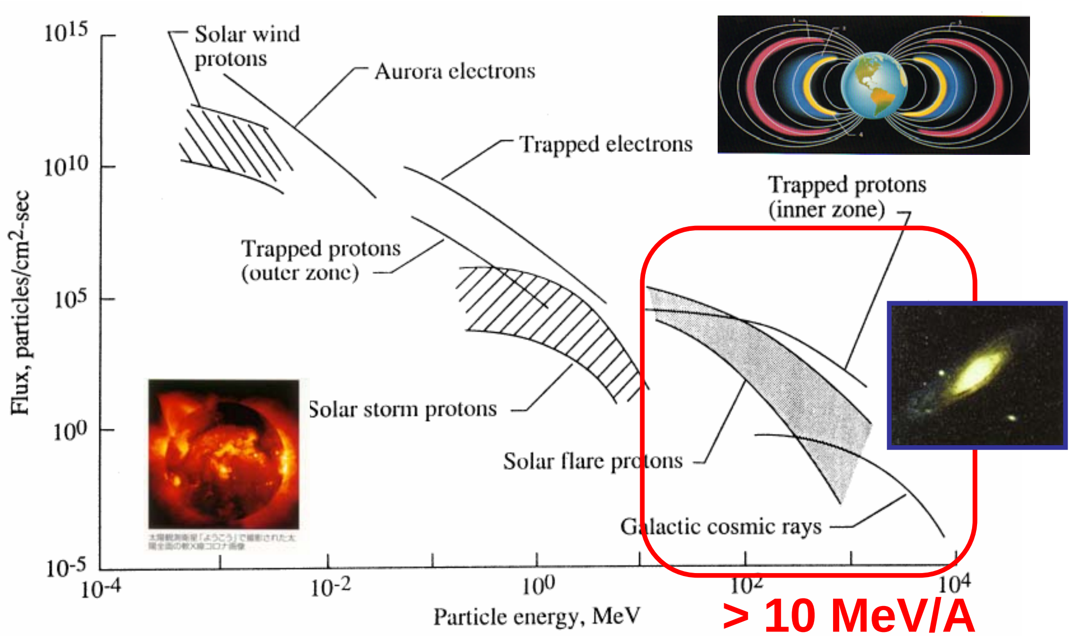
The SEUs (Soft errors) have recently been recognized as **a key reliability concern** for many current and future silicon-based integrated circuit technologies.

Physics related for SEU phenomena

Multi-physics & Multi-scale simulation



Cosmic-ray environment

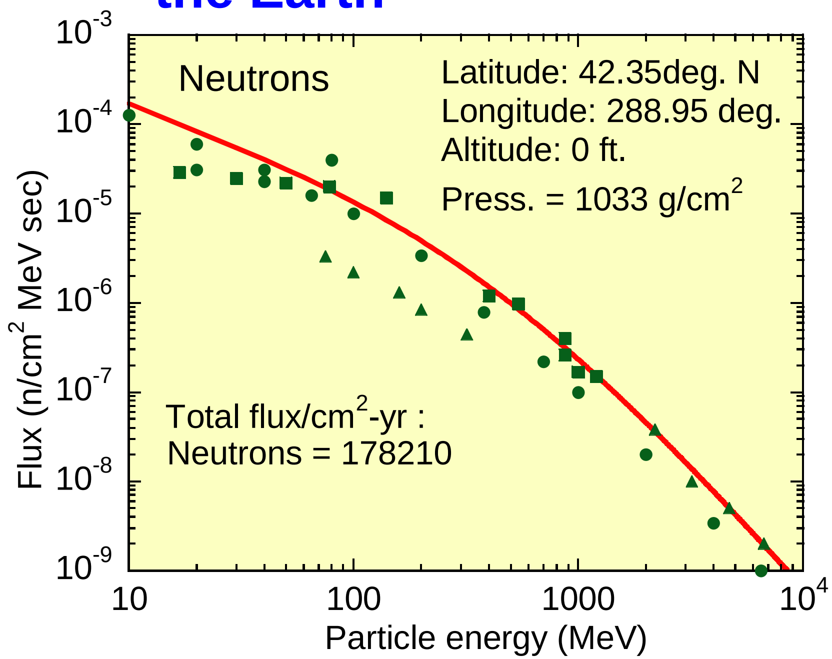


Cosmic-rays in Space

- **protons(92%),** alphas(6%), and HI (2%) in Galactic cosmic rays
- **protons** and electrons trapped in Van Allen belt
- **protons** from Solar flare

Neutron flux @Tokyo
about 12 n/cm² h
for above 10 MeV

Secondary cosmic-ray neutrons at sea level on the Earth

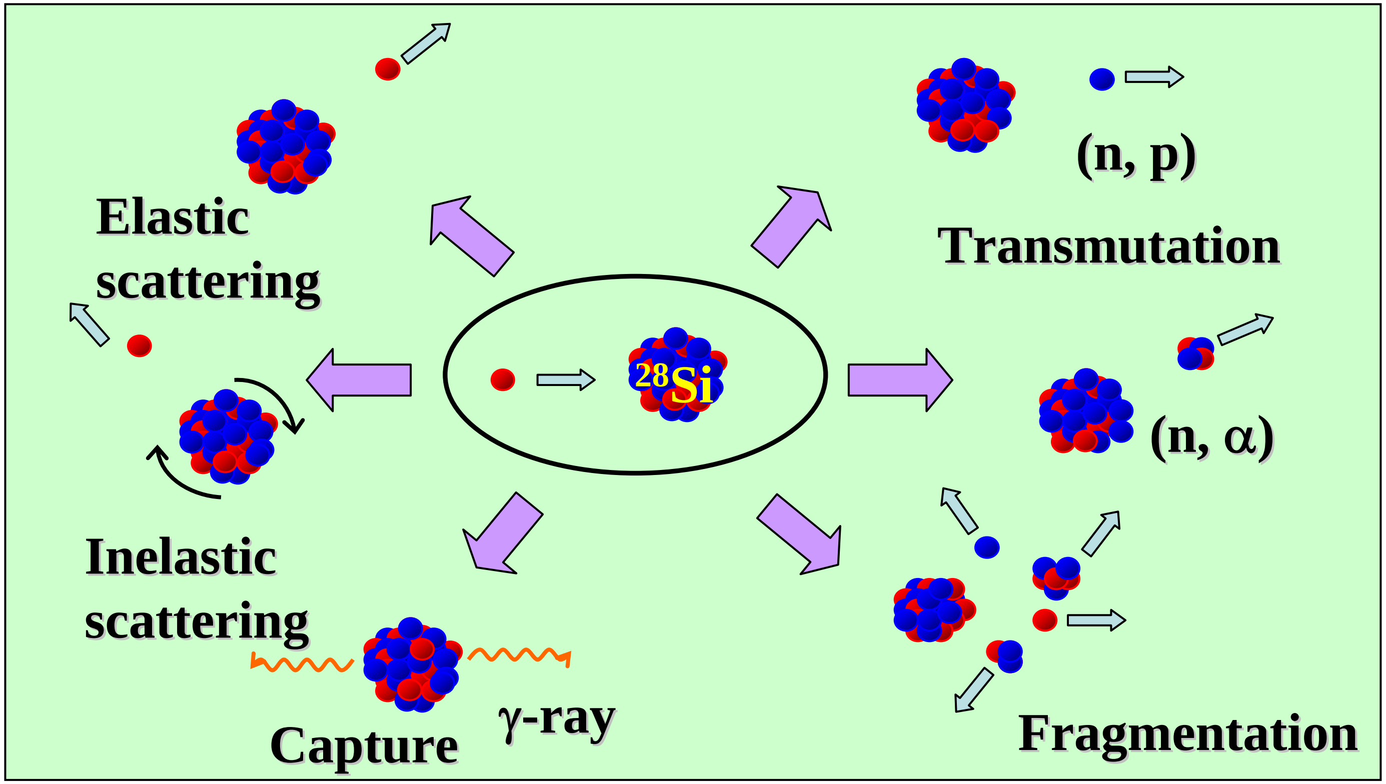


J.F. Ziegler, IBM J. Res. Develop. Vol. 40, No. 1 (1996), p. 19

Nuclear processes relevant to SEUs

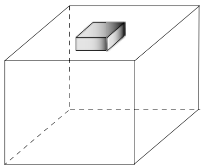
- **Production of secondary charged particles and fragments via nuclear reactions with a silicon nucleus**

- **Data of their energy and angular distributions are necessary in the incident energy range up to several GeV.**



Semi-empirical model

This model calculates nucleon-induced SEU cross section using experimental heavy-ion induced SEU data.



Barak et al., IEEE NS Vol. 43, No. 3, pp. 979-984 (1996).
Barak, IEEE NS Vol. 47, No. 3, pp. 545-550 (2000).

$$\sigma_{SEU}(E_{in}) = N_{Si}\cdot\sigma_N(E_{in})\int g(E_{in},E_d,d)\sigma_{HI}(E_d)dE_d$$

$$= N_{Si}\cdot\sigma_N(E_{in})\cdot V_{\mathrm{int}}\cdot\int g(E_{in},E_d,d)h(E_d)dE_d$$

The number of nuclear reactions in a reaction volume per unit flux

$$\sigma_N(E_{in}) = \sigma_{el.}(E_{in}) + \sigma_{react.}(E_{in})$$

Distribution function of the energy deposited in a sensitive volume (*d*: sensitive depth)

Dependence of charge collection efficiency on deposited energy

Normalized Heavy-ion SEU data

$$h(E_d) = \sigma_{HI}(E_d)/\sigma_{HI}^{\infty} = 1-\exp\left\{-\left[\frac{E_d-E_0}{W}\right]^s\right\}$$

$$E_d = d\cdot LET$$

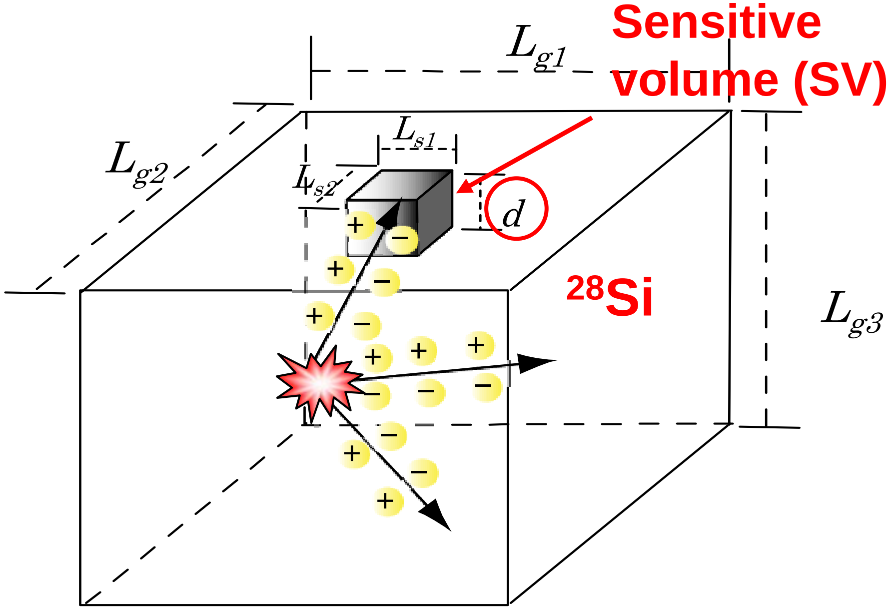
Weibull function

Monte Carlo calculation

$$\sigma_{SEU}(E_{in}) = \int \sigma_{ED}(E_{in}, E_d, SV) \cdot h(E_d) dE_d$$

$$\sigma_{ED}(E_{in}, E_d, SV) \equiv N_{Si} \cdot V_{\text{int}} \cdot \sigma_{reac}(E_{in}) \cdot g(E_{in}, E_d, d)$$

Rectangular parallelepiped geometry



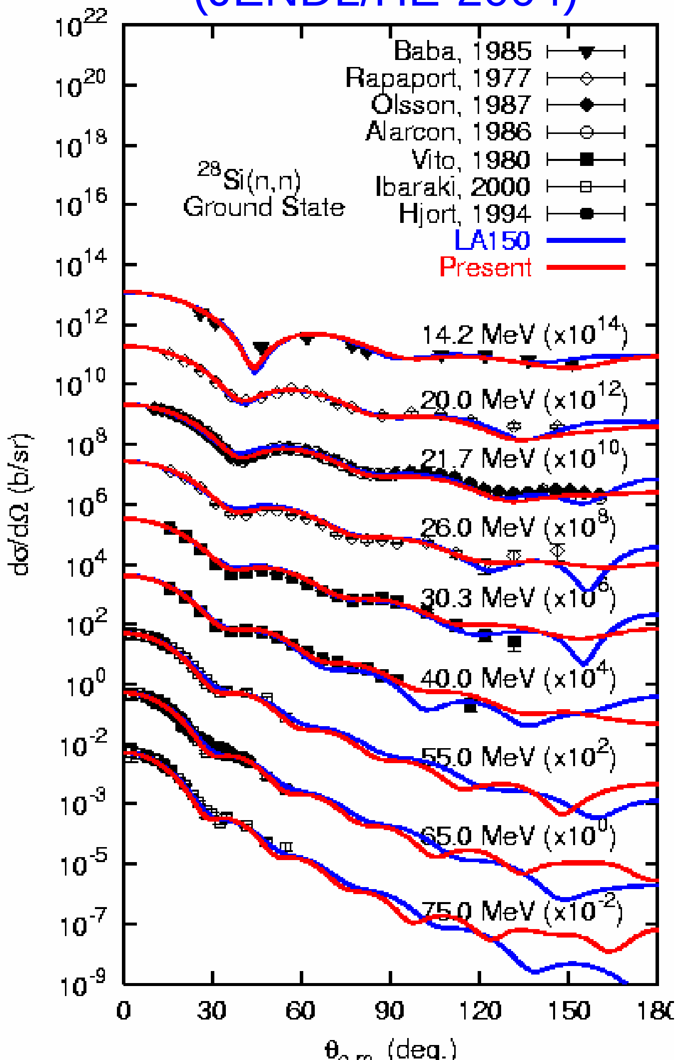
- Random sampling of a reaction point
- Nuclear reaction event generation (secondary ion, energy and angle) using ***nuclear reaction database created by QMD/GEM calculation and JENDL/HE-2004 data for elastic scattering***

Up to 1 GeV

- Energy deposition due to secondary ion using ***dE/dx and range calculated by SRIM code***

Nuclear reaction database (I): Elastic and Reaction products

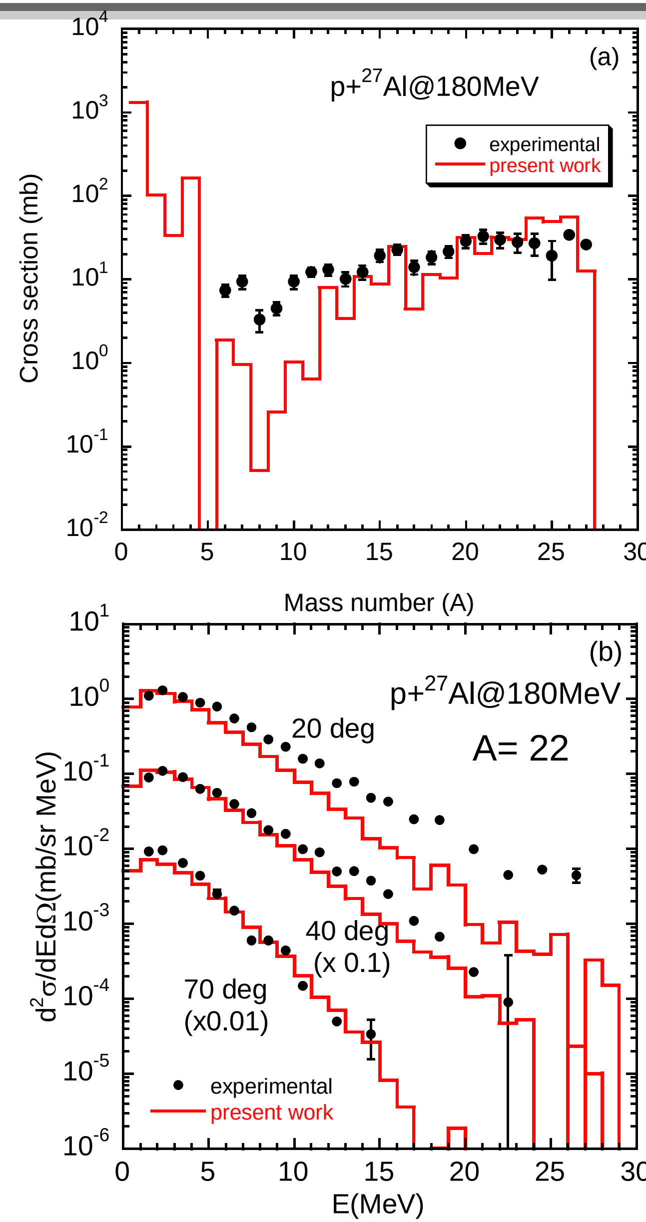
Neutron elastic scattering (JENDL/HE-2004)



JENDL/HE-2004:

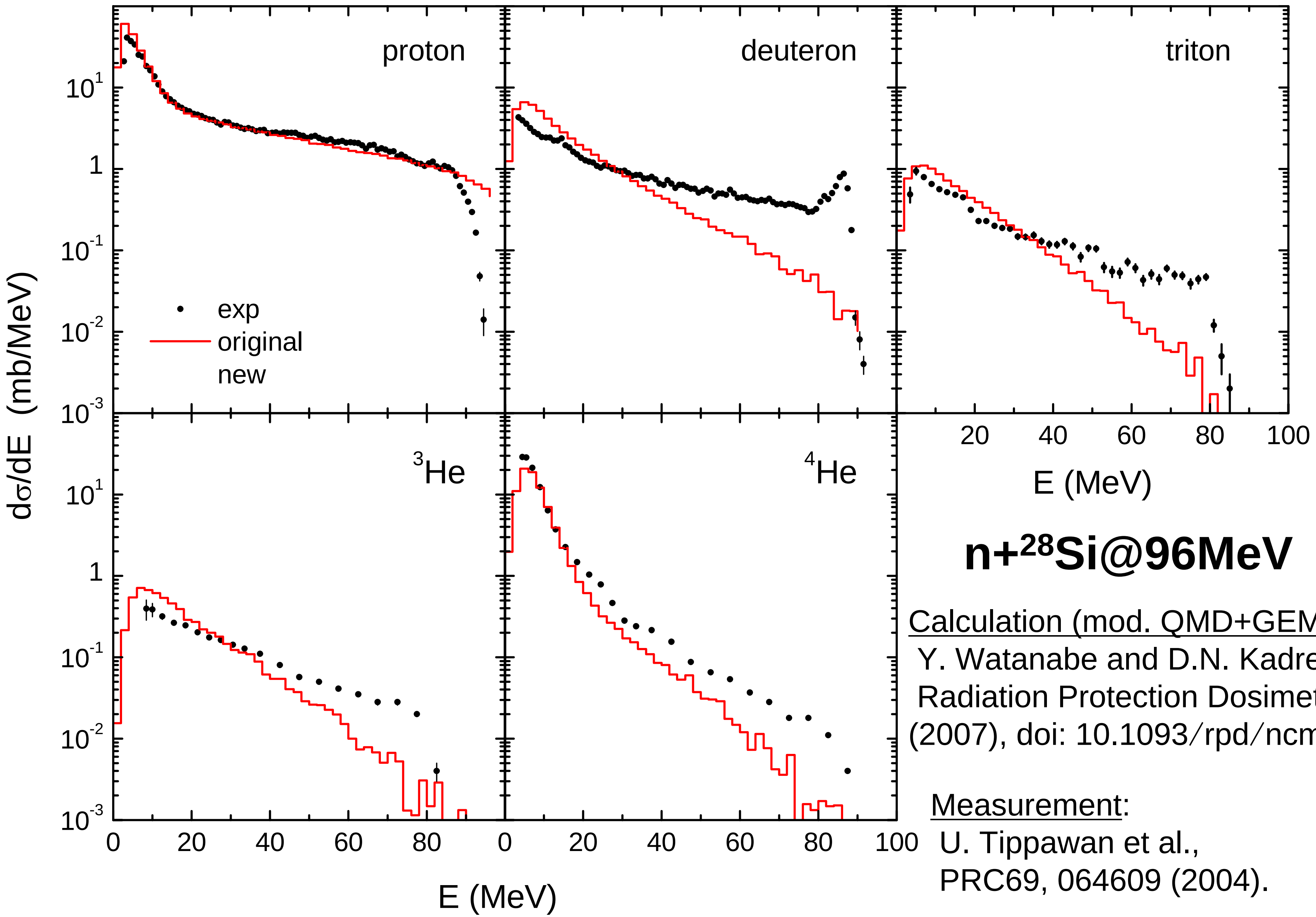
Y. Watanabe et al., AIP Conference Proc. 764 (2005), pp. 326

Reaction products



Exp. Ref.: K. Kwiatkowski et al. PRL 50, 1648 (1983)

Nuclear reaction database (II): Light ions



n+^{28}Si@96MeV

Calculation (mod. QMD+GEM):
Y. Watanabe and D.N. Kadrev
Radiation Protection Dosimetry
(2007), doi: 10.1093/rpd/ncm010

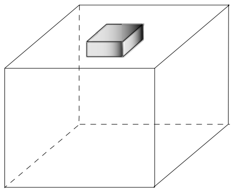
Measurement:
U. Tippawan et al.,
PRC69, 064609 (2004).

Comparison with experimental data (I)

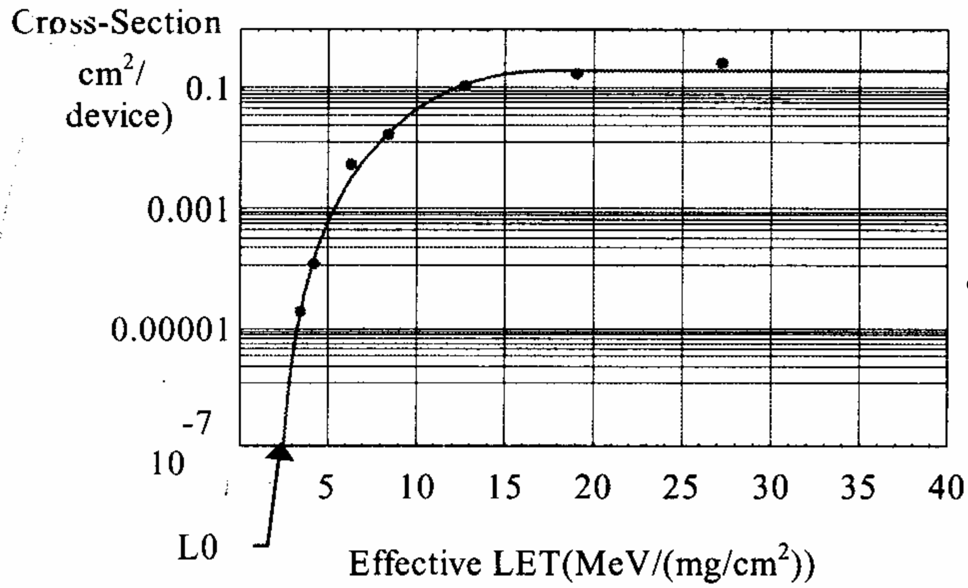
32K x 8 bit SRAM (HM62256)

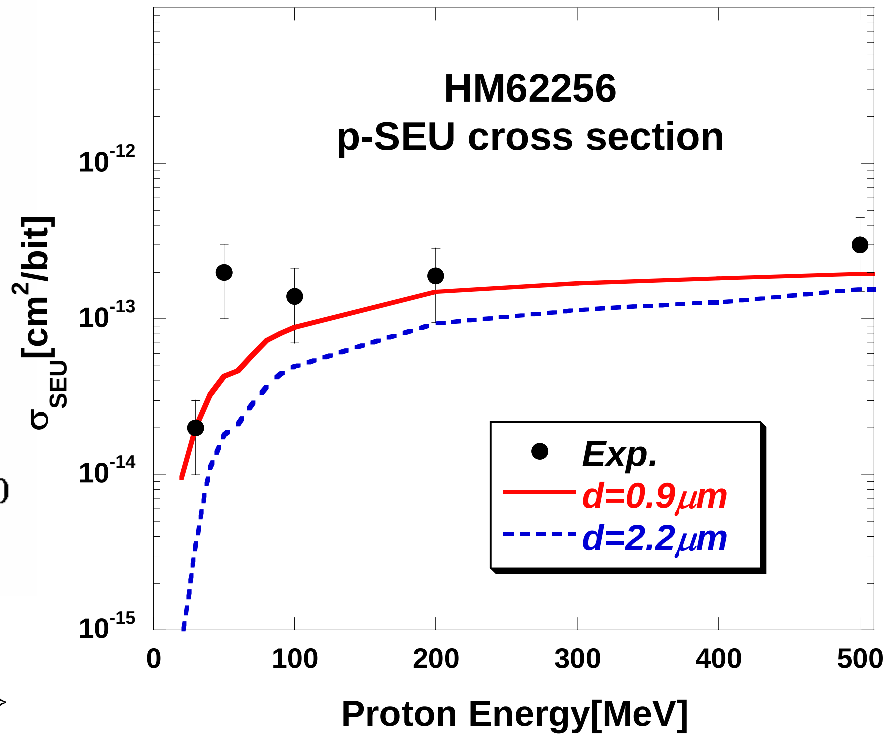
Sensitive area = $\sigma_{HI}^{\infty} = 76.2\mu m^2$

d = 2.2 or 0.9 μm



HI-SEU cross section





$$h(E_d) = \sigma_{HI}(E_d)/\sigma_{HI}^{\infty} = 1 - \exp\left\{-\left[\frac{E_d - E_0}{W}\right]^s\right\}$$

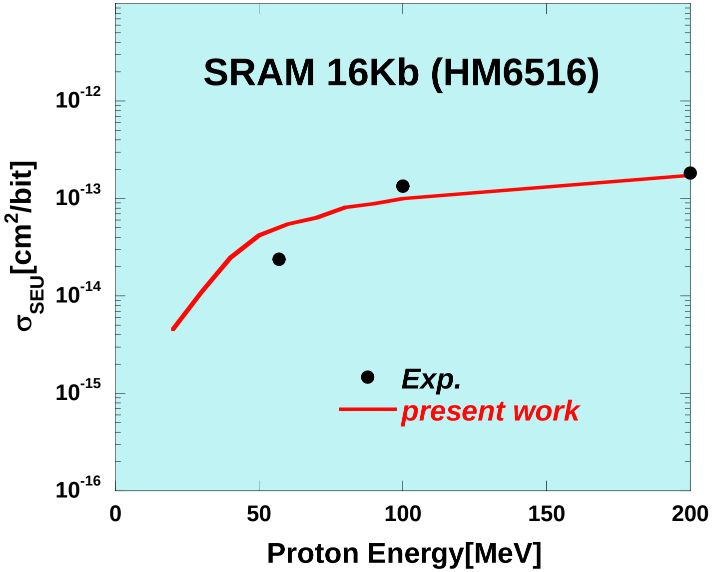
$$E_d = d \cdot LET$$

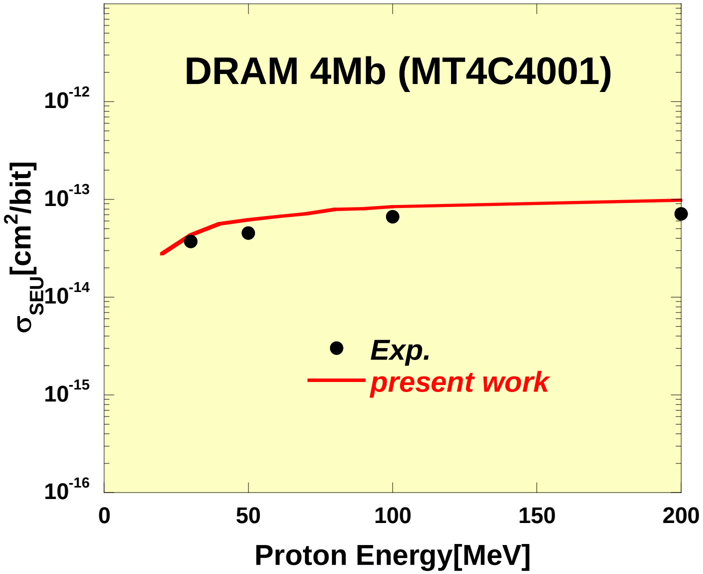
Ref.) P.D. Bradley and E. Normand, IEEE NS Vol. 45, No.6 pp. 2929-2940 (1998)

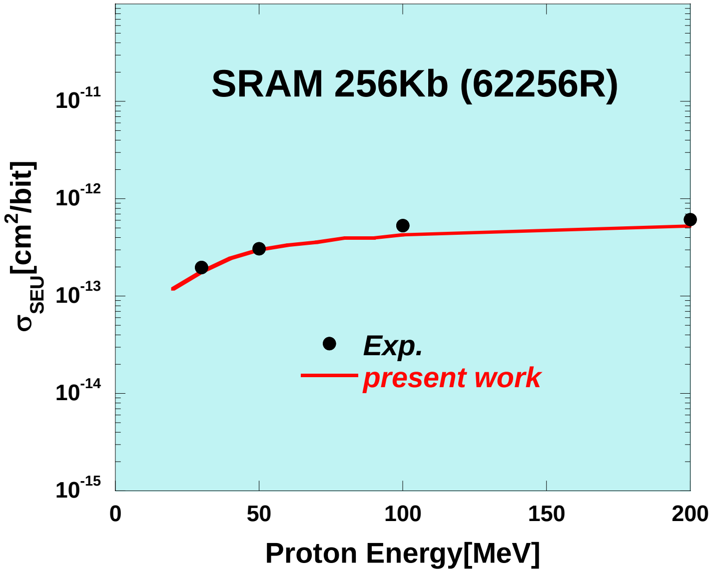
Comparison with experimental data (II)

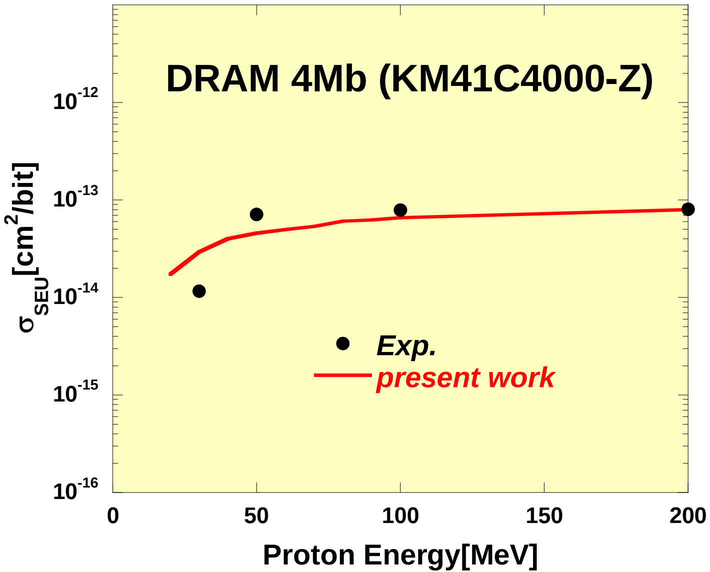
Sensitive depth = 2 μm

Exp.) P. Calvel et al., IEEE NS 43, No.6 (1996) 2827.

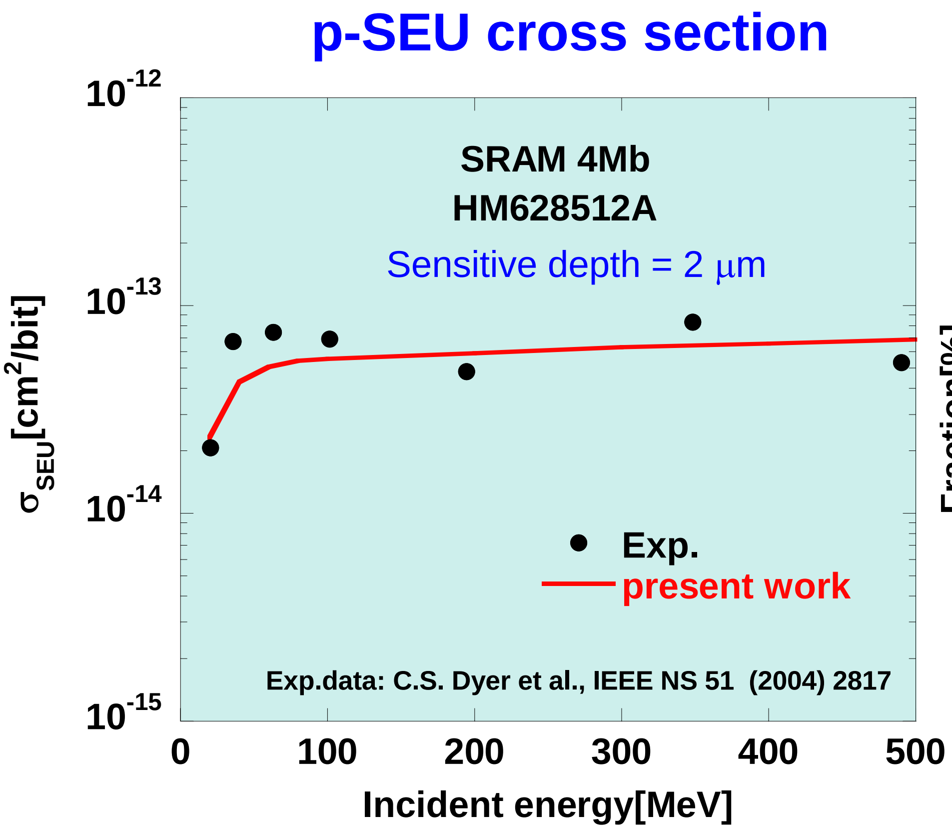


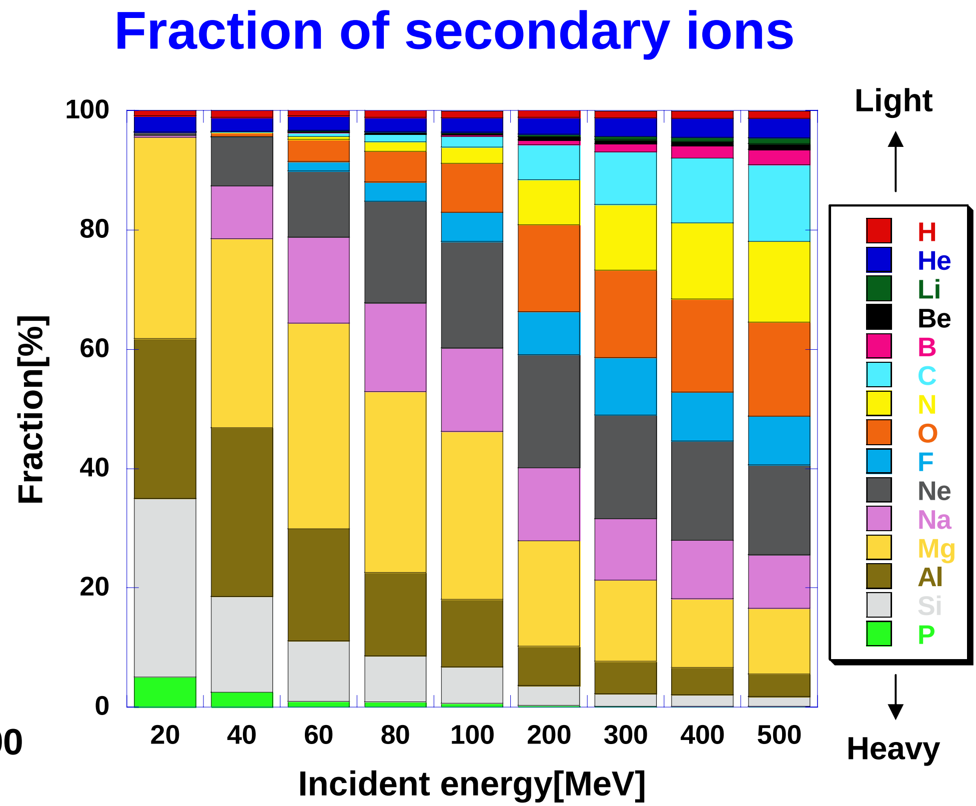






Contribution from each secondary ion to SEU (III)





- The calculated SEU cross section reproduces the experimental data reasonably well.
- Heavy secondary ions with high LET (Si, Al, Mg) contributes mainly to SEU at low energies, while relative contribution from light ions with low LET (C, N, O) becomes large as the incident energy increases.

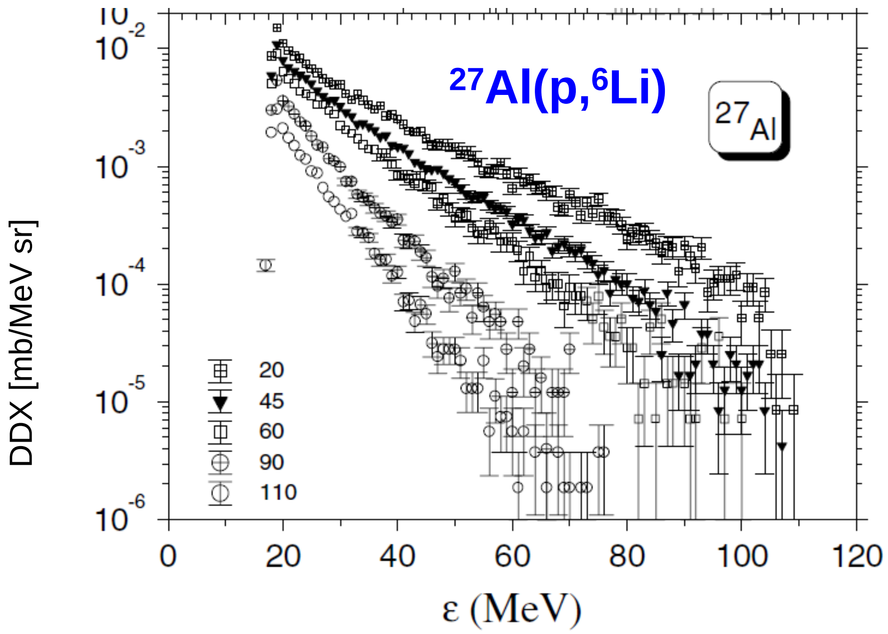
Summary

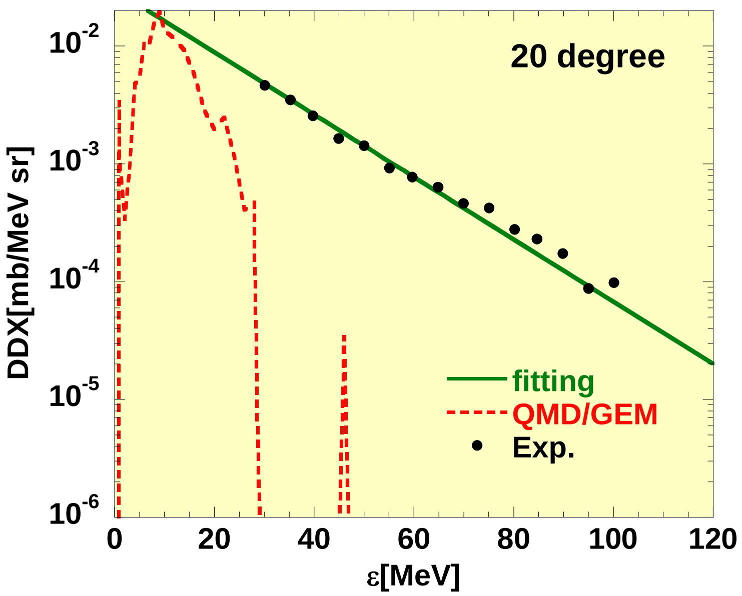
- Role of nuclear physics to understand nucleon-induced single-event upset (SEU) phenomena and to estimate SEU cross sections
- Calculation of SEU cross sections using the semi-empirical model based on the sensitive volume concept
- Impact of nuclear data on SEU simulation:
  Incident energy dependence of secondary ions leading to SEU

Future requirement for nuclear data

- More measurements of DDXs of secondary ions over the wide mass range are required for testing the predictions of reaction models and their refinement. (Target: Si and O)

H. Machner et al., PRC 73, 044606 (2006): He, Li, Be, B from 200 MeV p+Al





- Further refinement of the models is necessary to provide reliable nuclear reaction data

Thank you for your attention.