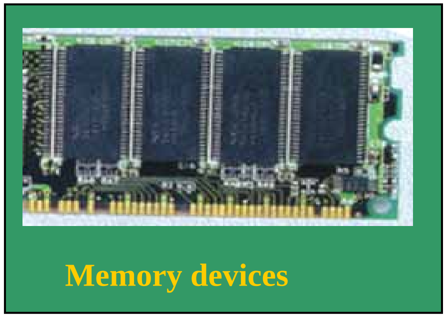
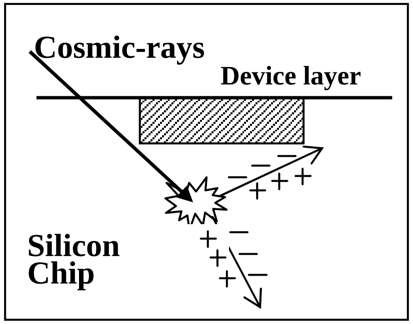
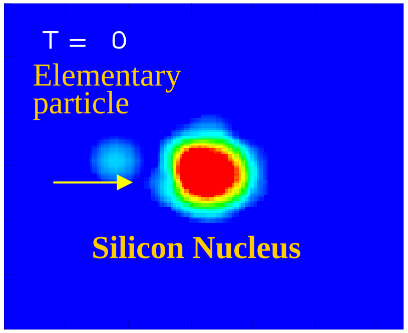
Presented at Nuclear Data Symposium 2006,
Tokai, Japan, January 26, 2007

Nuclear data relevant to single event upsets in semiconductor memories induced by cosmic-ray neutrons and protons

- Role of nuclear data in our IT society -







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In cooperation with
Akihiro Kodama and Kouta Nishijima

Introduction

Single-Event Upset (SEU)

- **One of the radiation effects caused in microelectronic devices** (e.g., semiconductor memory devices) used in various radiation 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" effects** caused by a single ionizing particle

⇒ **Soft Error or Soft Failure**

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

Forbes.com

November 13, 2000

Note that the cosmic-ray induced SEU was predicted by Ziegler@IBM and Landford@Yale Univ. (1979).

Sun Screen

THE MYSTERIOUS GLITCH has been popping up since late last year. At a new Web company in San Francisco, a telecommunications company in the Midwest, a Baby Bell in Atlanta, an Internet domain registry on the East Coast--for no apparent reason, **high-end servers made by Sun Microsystems suddenly crashed**.

....

Sun says it has finally figured out what's wrong. **It is an odd problem involving stray cosmic rays** and memory chips in the flagship Enterprise server line, whose models are priced at $50,000 to more than $1 million. Yet Sun won't fix all of the servers it has sold; instead it will make repairs when it deems them necessary.

http://www.forbes.com/forbes/2000/1113/6613068a_print.html

Rough estimation of SER in our daily life

1000 FIT = mean time to failure : **114 year (=10^6 hr) / device**

- Cell phone

  4Mbit memory with **1000FIT/1Mbit** on board

  1 error / 28 year

- Network equipment having SRAM with **600FIT/1Mbit** on board

  High-end router : 10Gbit SRAM **1 error / 170 hours**

  100Gbit SRAM **1 error / 17 hours**

- Laptop PC in airplane

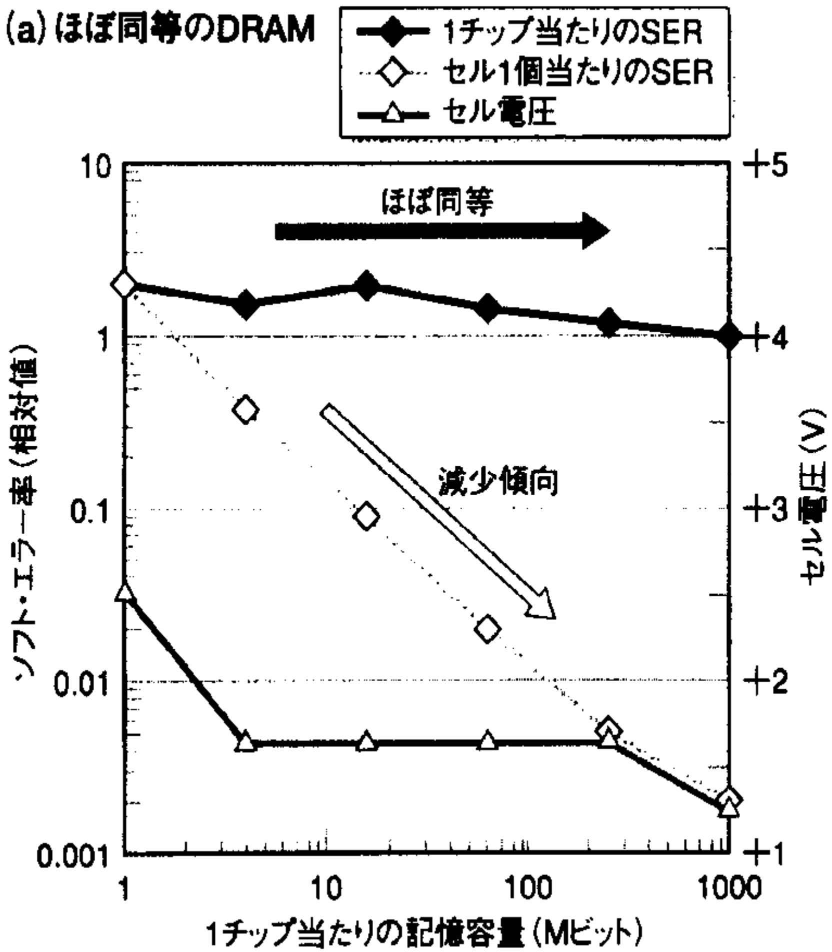
  600FIT/1Mbit → **100,000 FIT/1Mbit@10,000 m in altitude**

  256MB (2Gbit) memories on board **1 error / 5 hours**

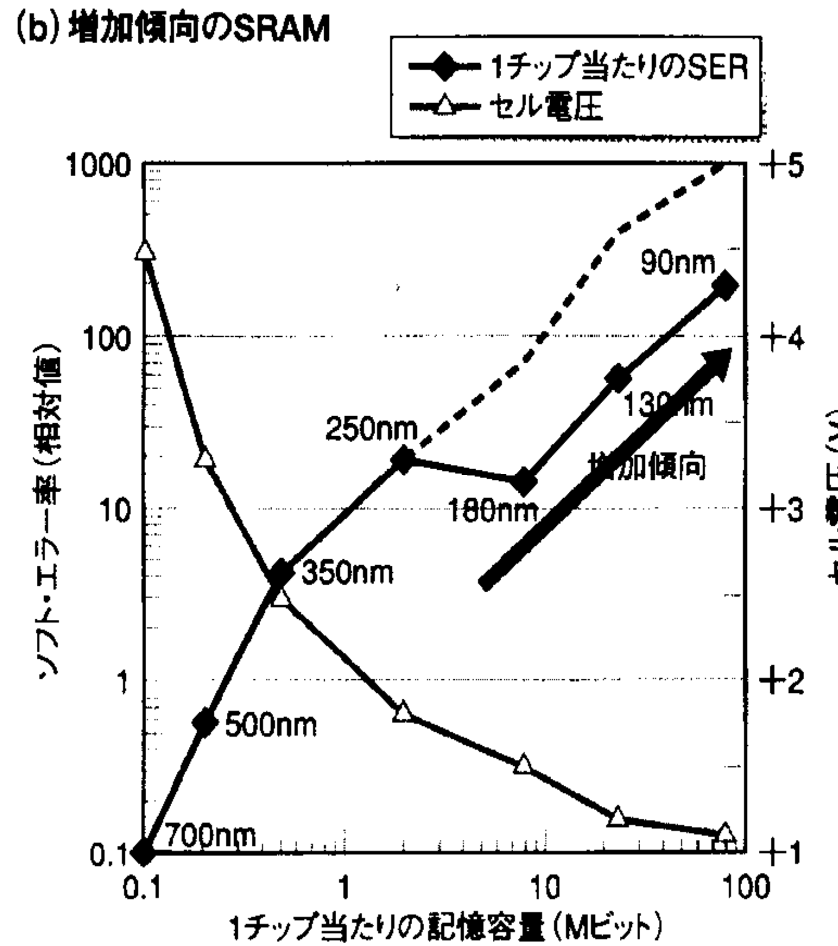
Source : http:/www.ednjapan.com/content/issue/2005/02/feature/feature02.html

Soft error rate in DRAM and SRAM

DRAM



SRAM



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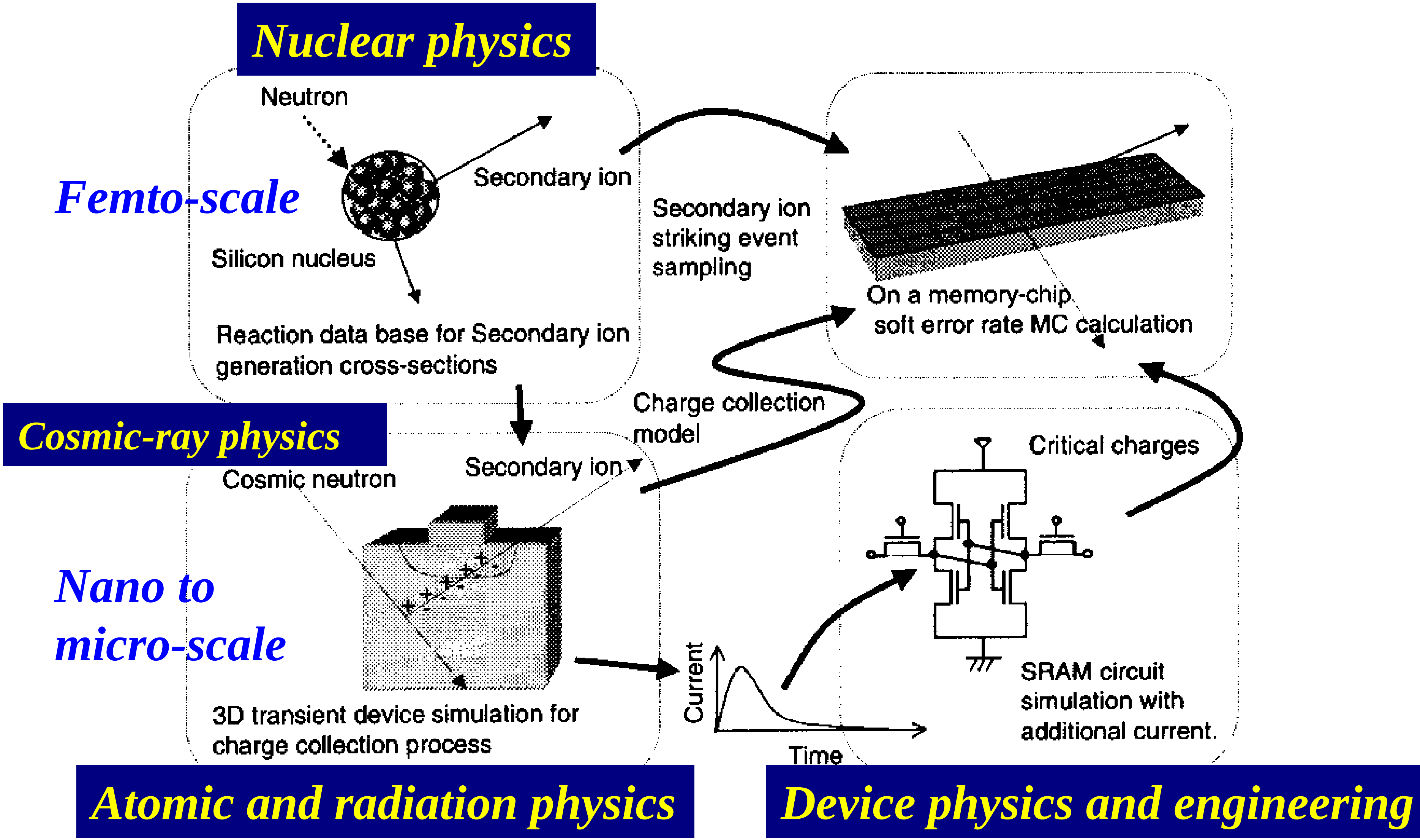
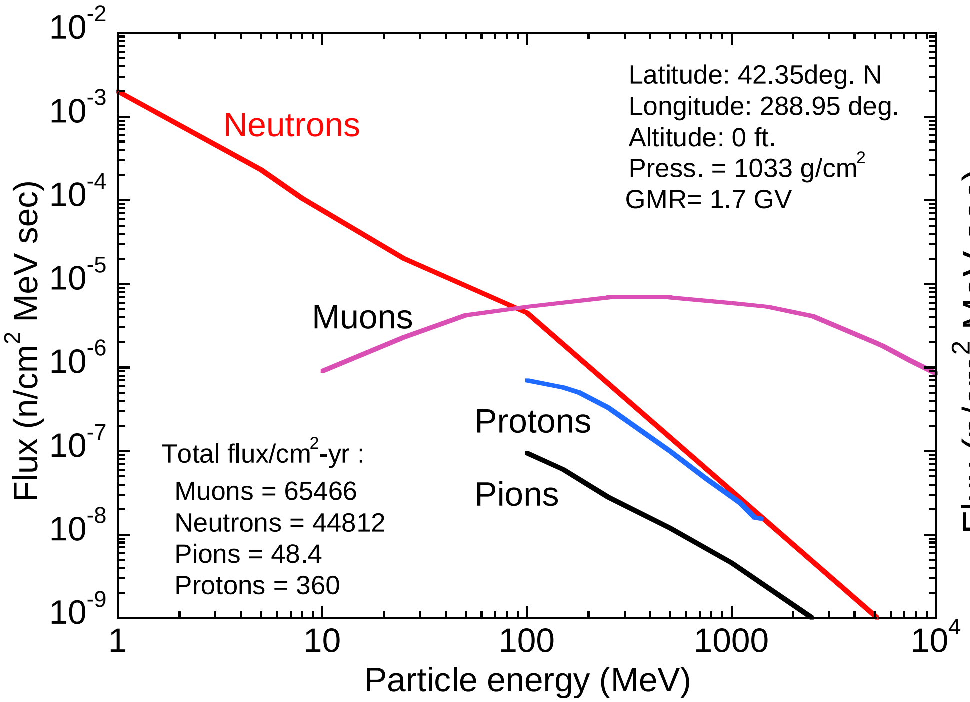
日経エレクトロニクス2005.7.4

Physics related for SEU phenomena

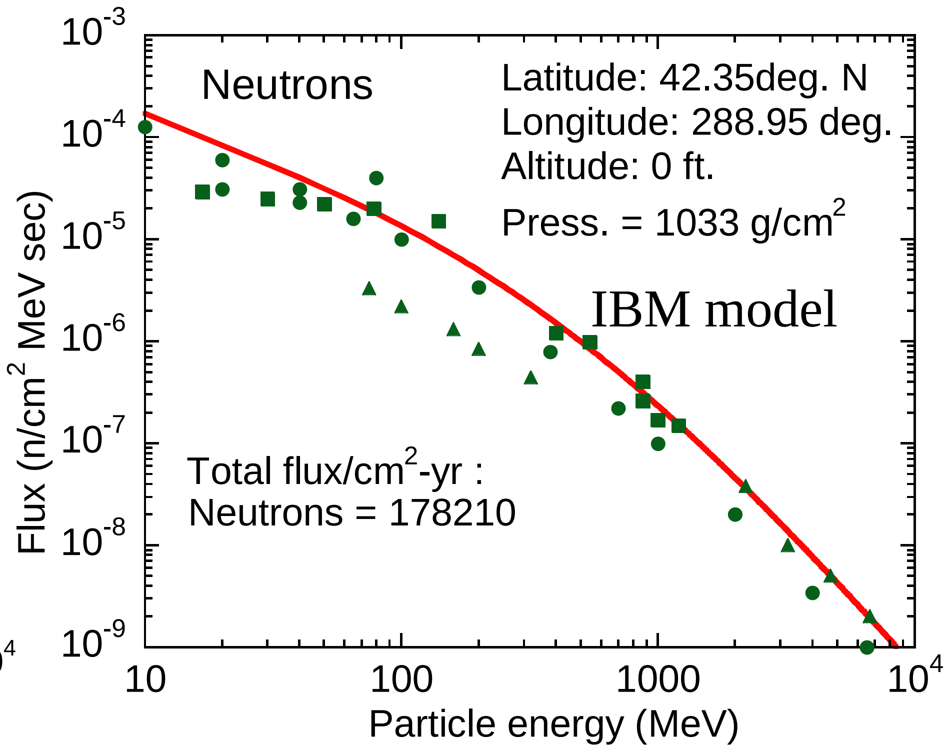
Multi-physics & Multi-scale simulation



Cosmic-ray environment on the earth



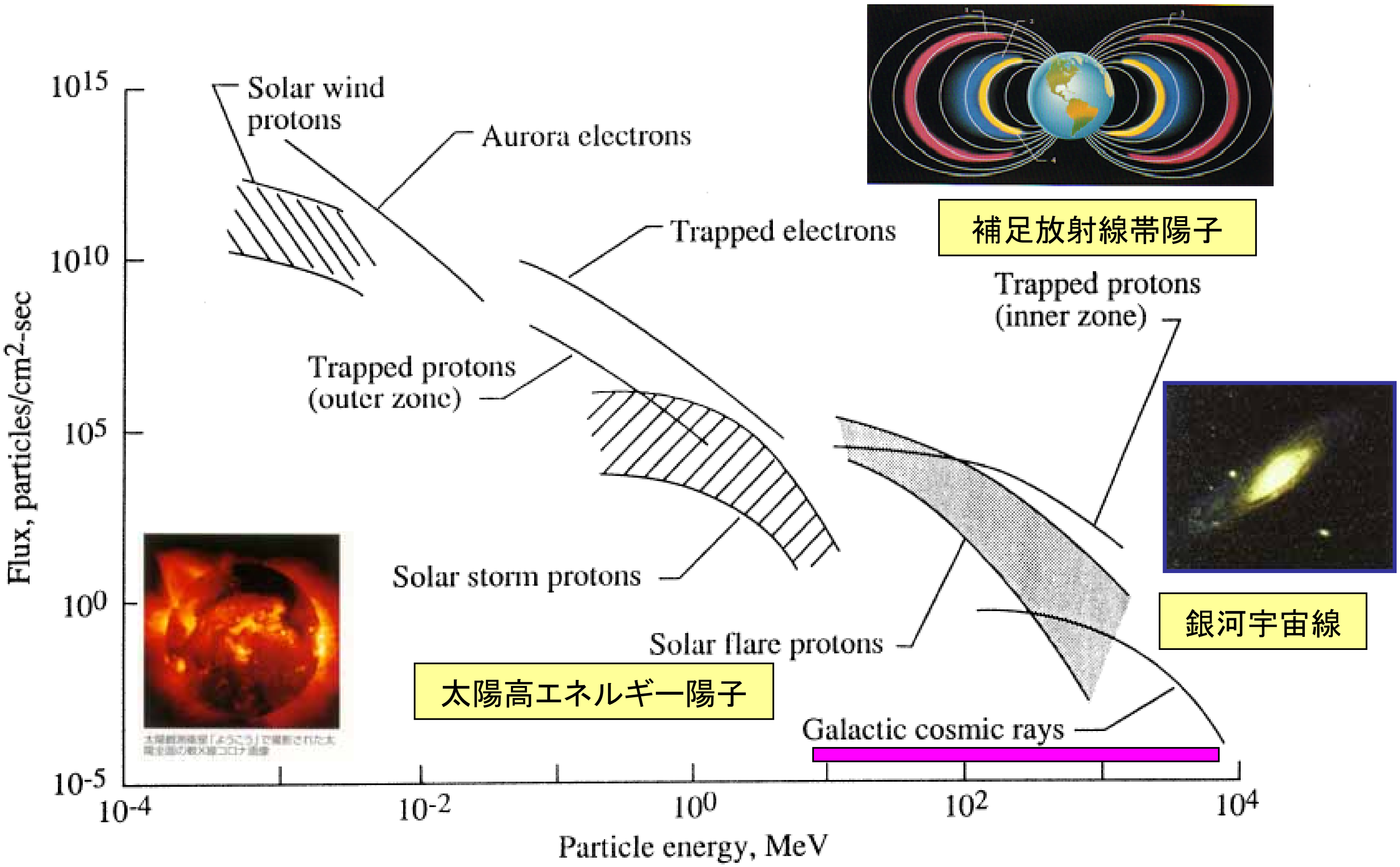
Sea level @ New York



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

Ref.) J.F. Ziegler, “Terrestrial cosmic rays”, IBM J. Res. Develop. Vol. 40, No. 1 (1996), p. 19

Radiation flux in Space

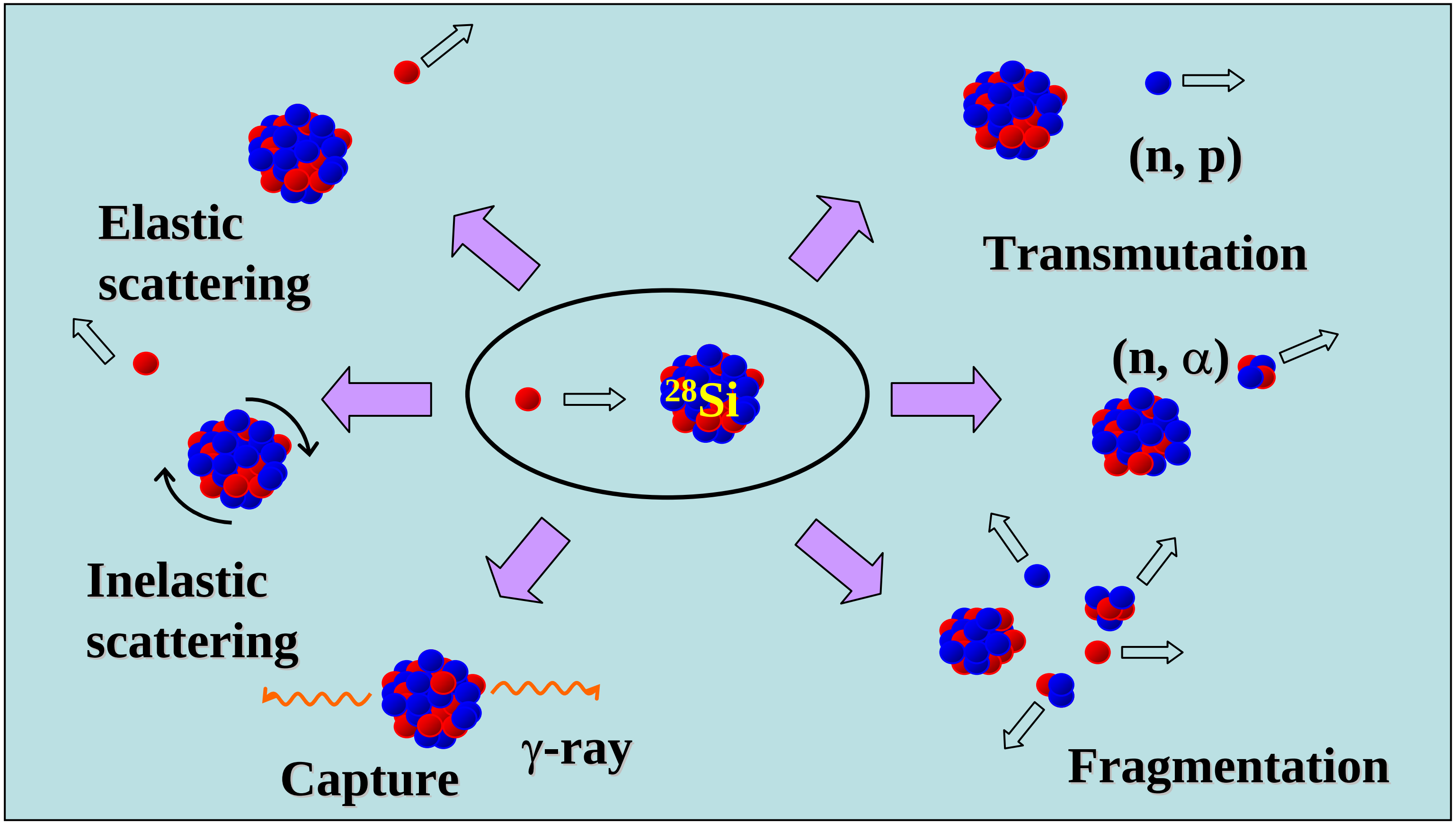


Ref.) K. Oishi, "Issues in space radiation shielding for linar base", JAERI-Conf95-016 (1995), p.125

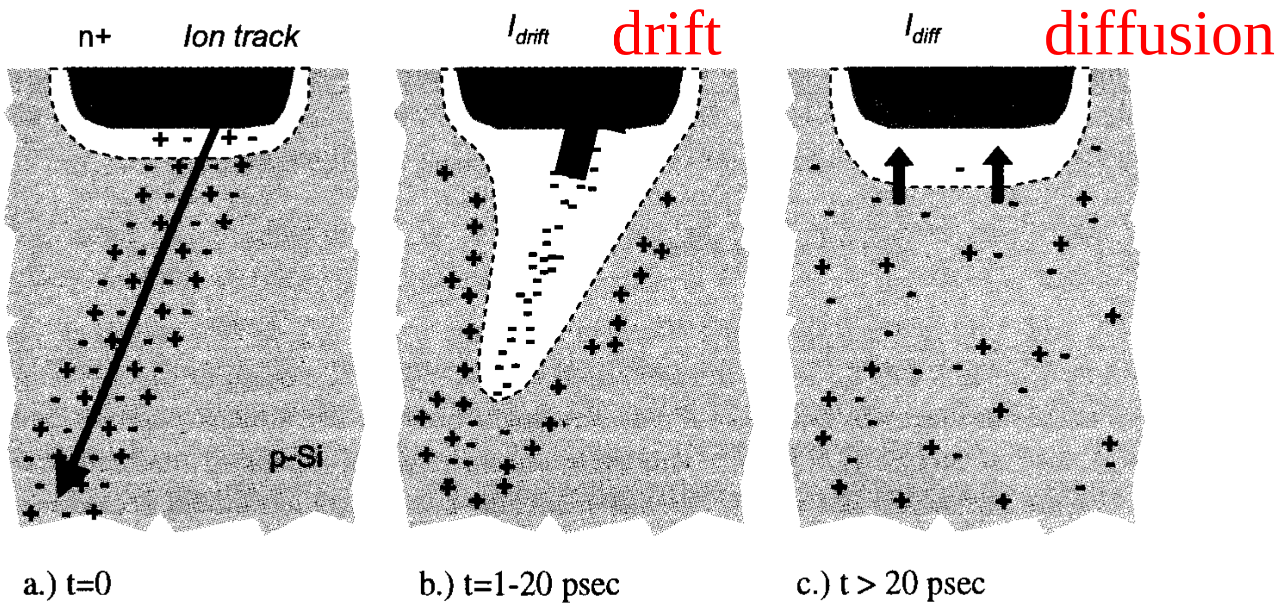
Nuclear processes relevant to SEUs

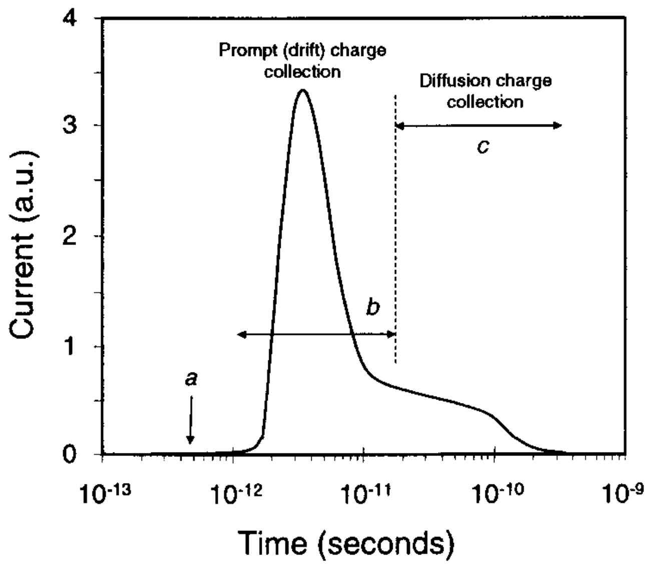
- **Production of secondary charged particles and fragments via nuclear reactions with a silicon nucleus**

- **Data of their energy and angular distributions are necessary.**



Charge collection in a silicon junction

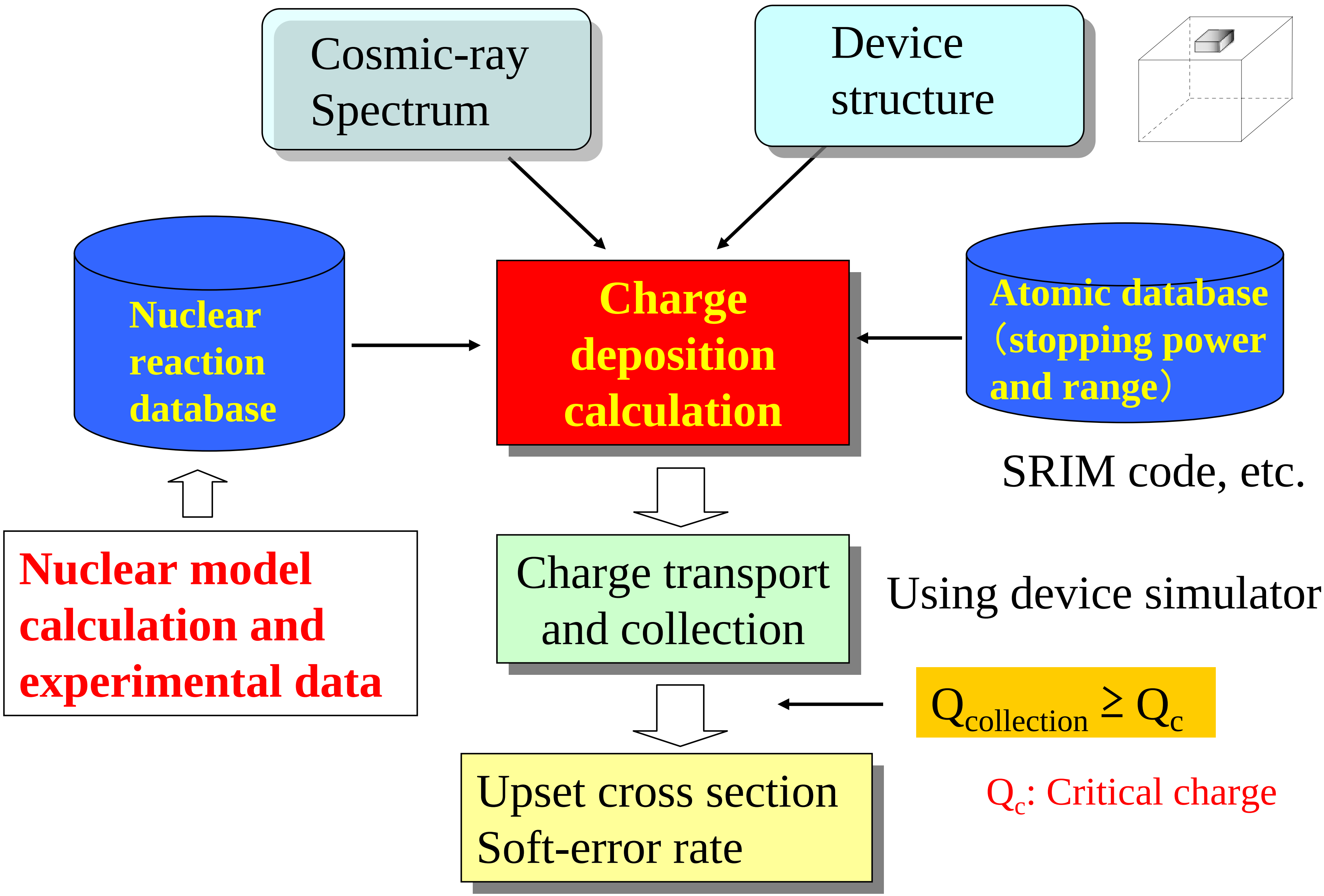




$$Q_{collection} = \int_0^{t_{max}} i(t)dt$$

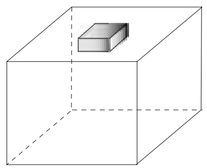
Ref.) Radiation effects and soft errors in integrated circuits and electronic devices, p.17

Flow chart of SEU simulation



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).

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

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

The number of nuclear reactions in ROI per unit flux

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

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

Dependence of charge collection efficiency on deposited energy

Normalized Heavy-ion SEU data

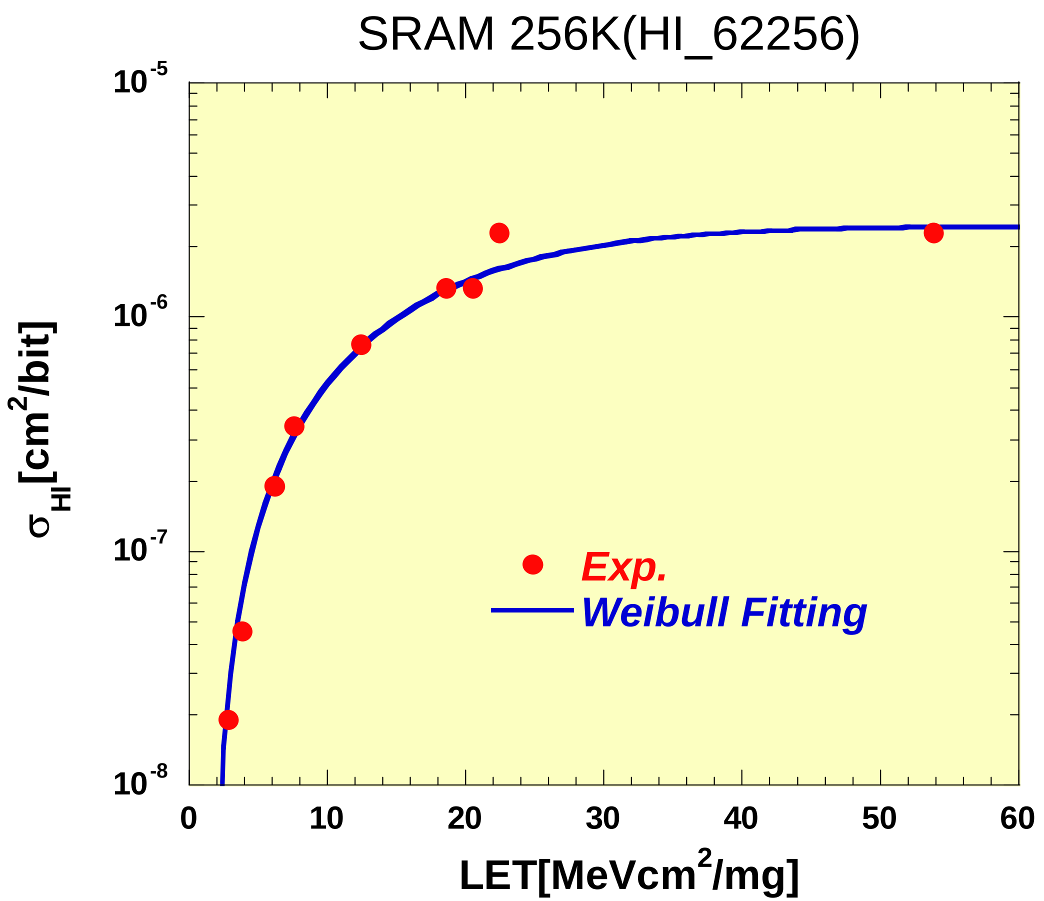
$$h(E_d) = \sigma_{HI}(E_d)/\sigma_{HI}^{\infty} = 1 - \exp\left\{-\left[\frac{E_d - E_0}{W}\right]^s\right\}$$

$$E_d = d \cdot LET$$

Weibull function

HI-induced SEU cross section

$$\sigma_{HI}(L) = \sigma_{HI}^{\infty}\left(1 - \exp\left\{-\left[\frac{L - L_0}{W}\right]^s\right\}\right)$$

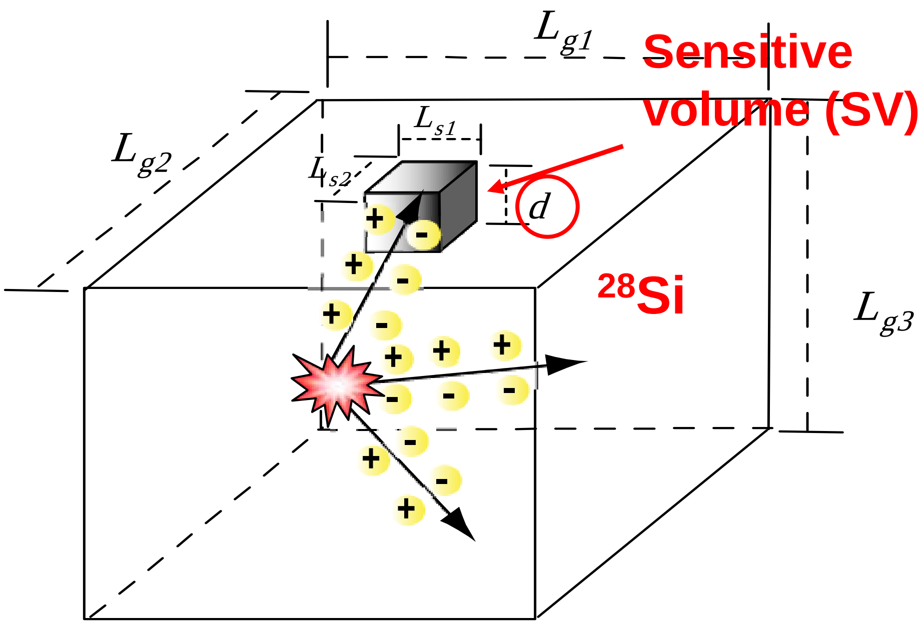


Monte Carlo calculation

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

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

Rectangular parallelepiped geometry



- Random sampling of a reaction point

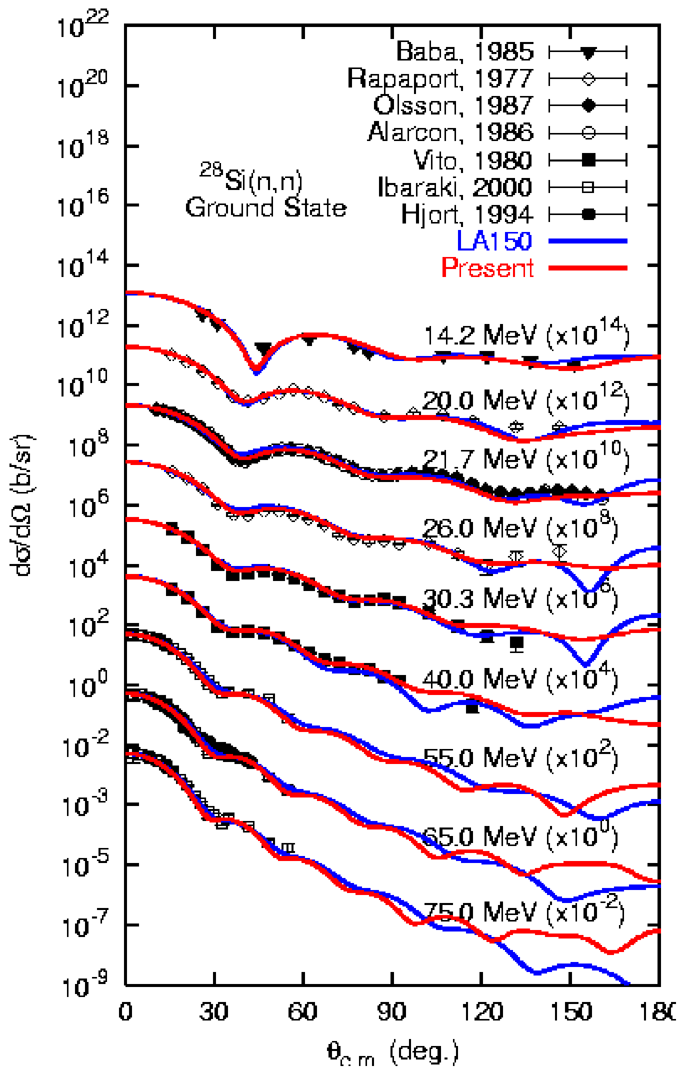
- Nuclear reaction event generation (secondary ion, energy and angle) using ***nuclear reaction database created by QMD/GEM calculation and JENDL/HE-2004 for elastic scattering (exclusive, inclusive)***

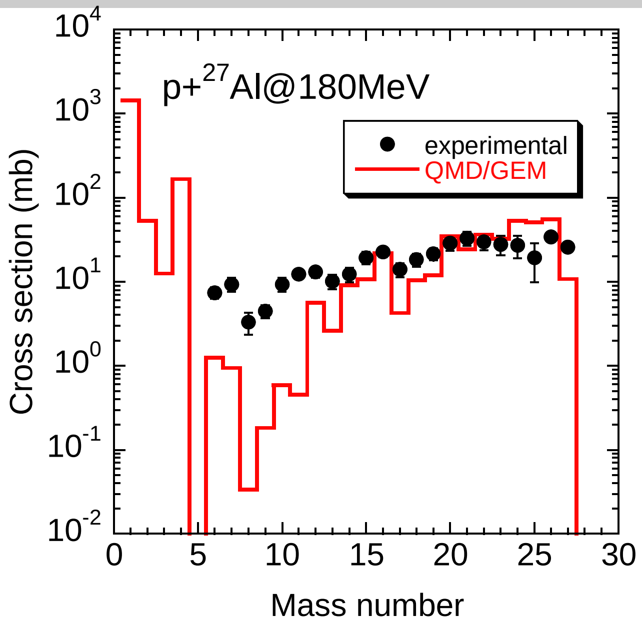
Up to 1 GeV

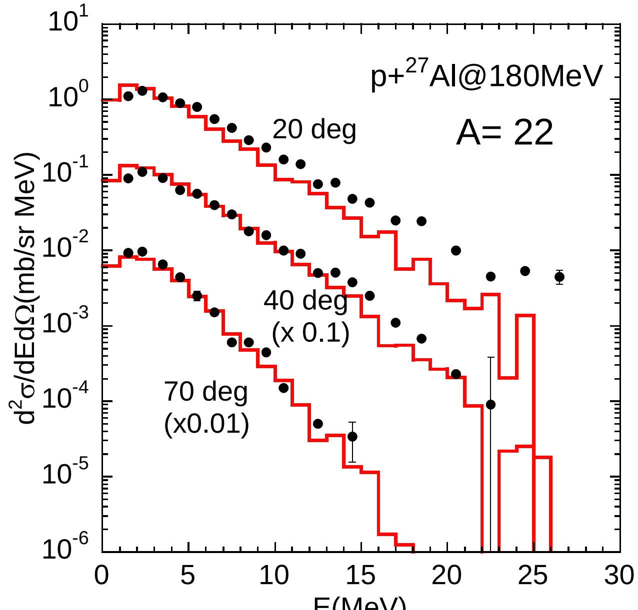
- Energy deposition due to secondary ion using ***dE/dx and range calculated by SRIM code***

Nuclear reaction database

Neutron elastic scattering
(JENDL/HE-2004)





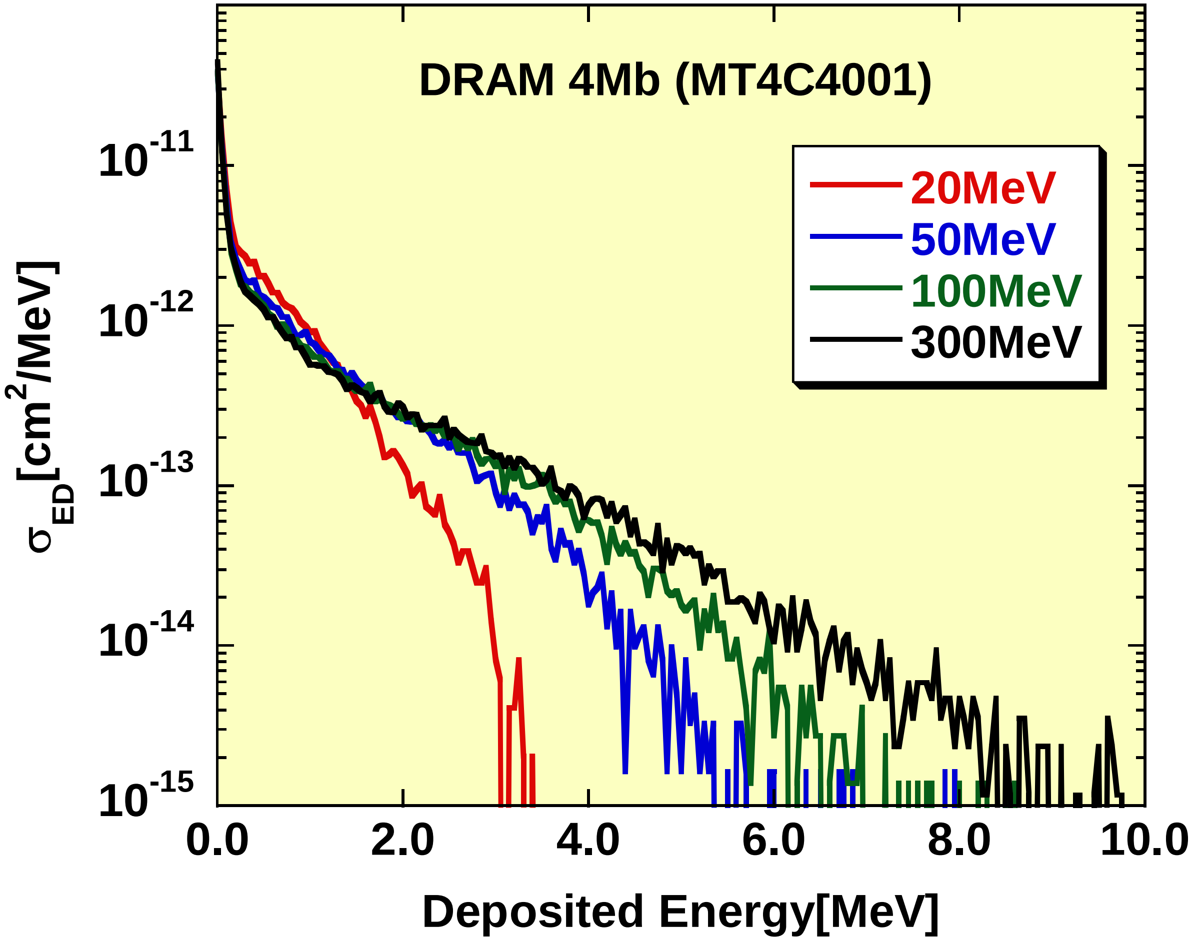


Ref.: K. Kwiatkowski et al.

PRL 50, 1648 (1983)

Incident energy dependence of energy deposition spectra

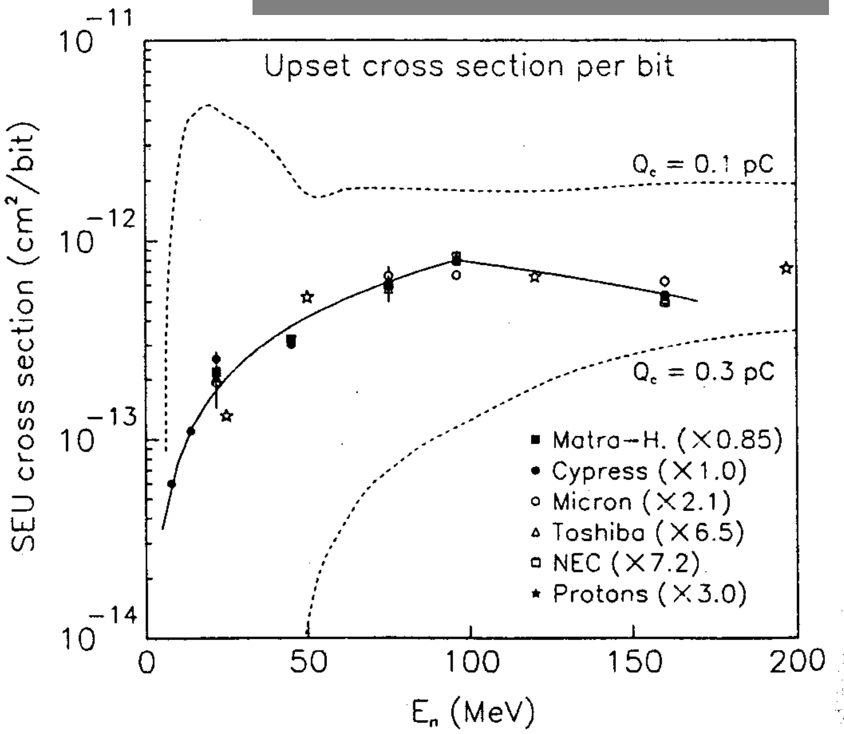
- Proton incidence
- Sensitive Volume : $V = \sigma_{HI}^{\infty} \cdot d = 5.57 \times 5.57 \times 2 \mu m^3$



Experimental SEU cross sections

SRAM

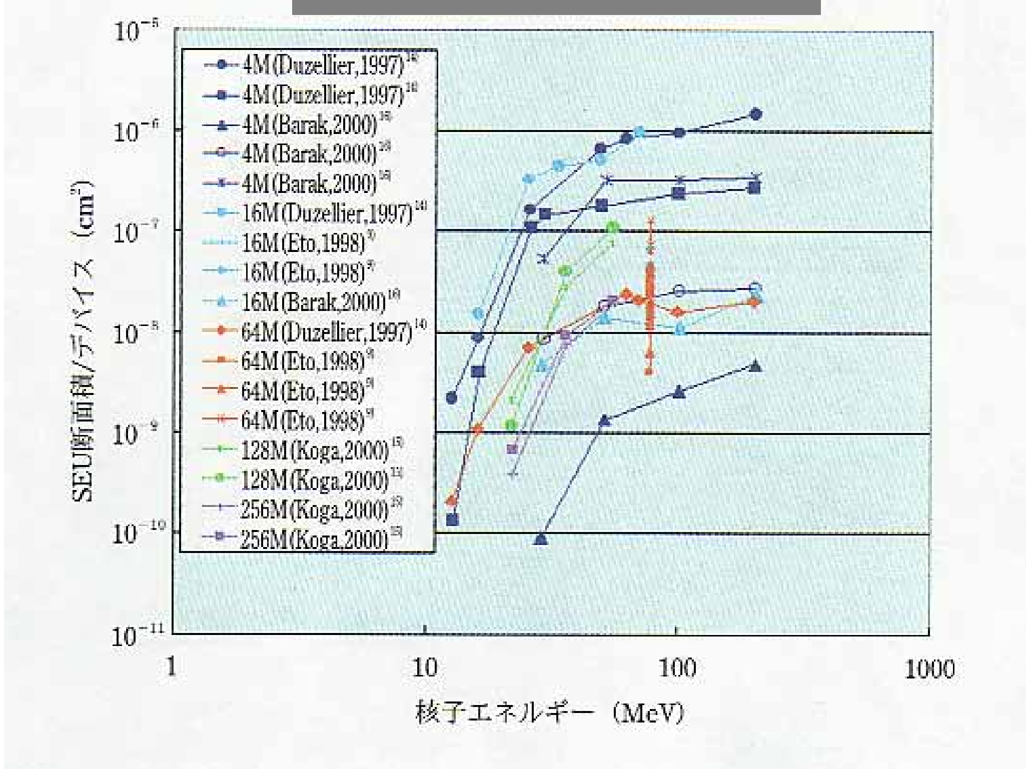
Neutron irradiation



Ref.) K. Johansson et al., IEEE Trans. Nucl. Sci. 45, 2519 (1998).

DRAM

Proton irradiation



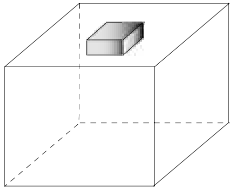
引用） 伊部ら、応用物理Vol.70, No.11 (2001)

Comparison with experimental data (I)

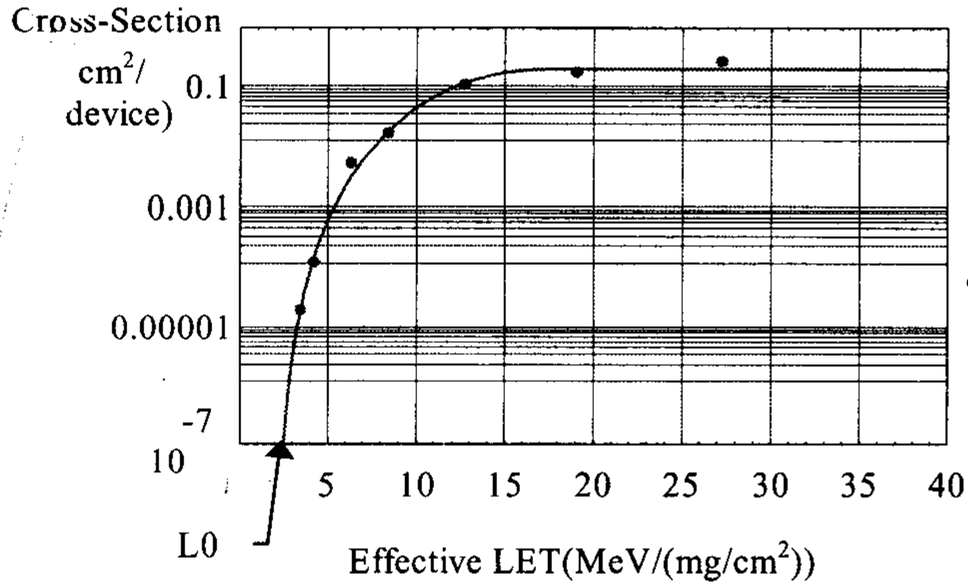
32K x 8 bit SRAM (HM62256)

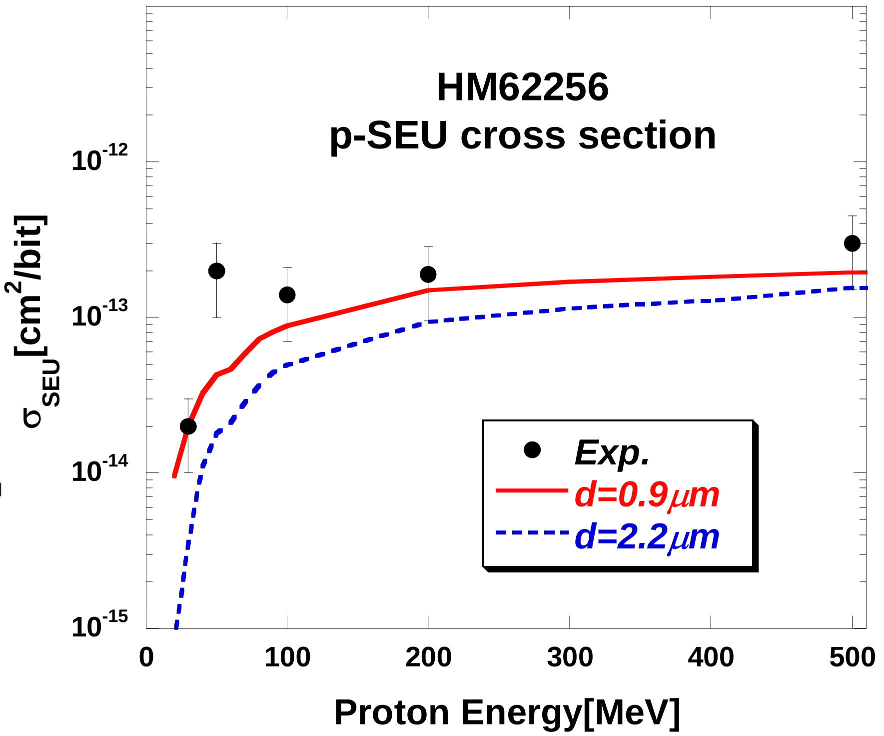
Sensitive area = $\sigma_{HI}^{\infty} = 76.2 \mu m^2$

d = 2.2 or 0.9 μm



HI-SEU cross section

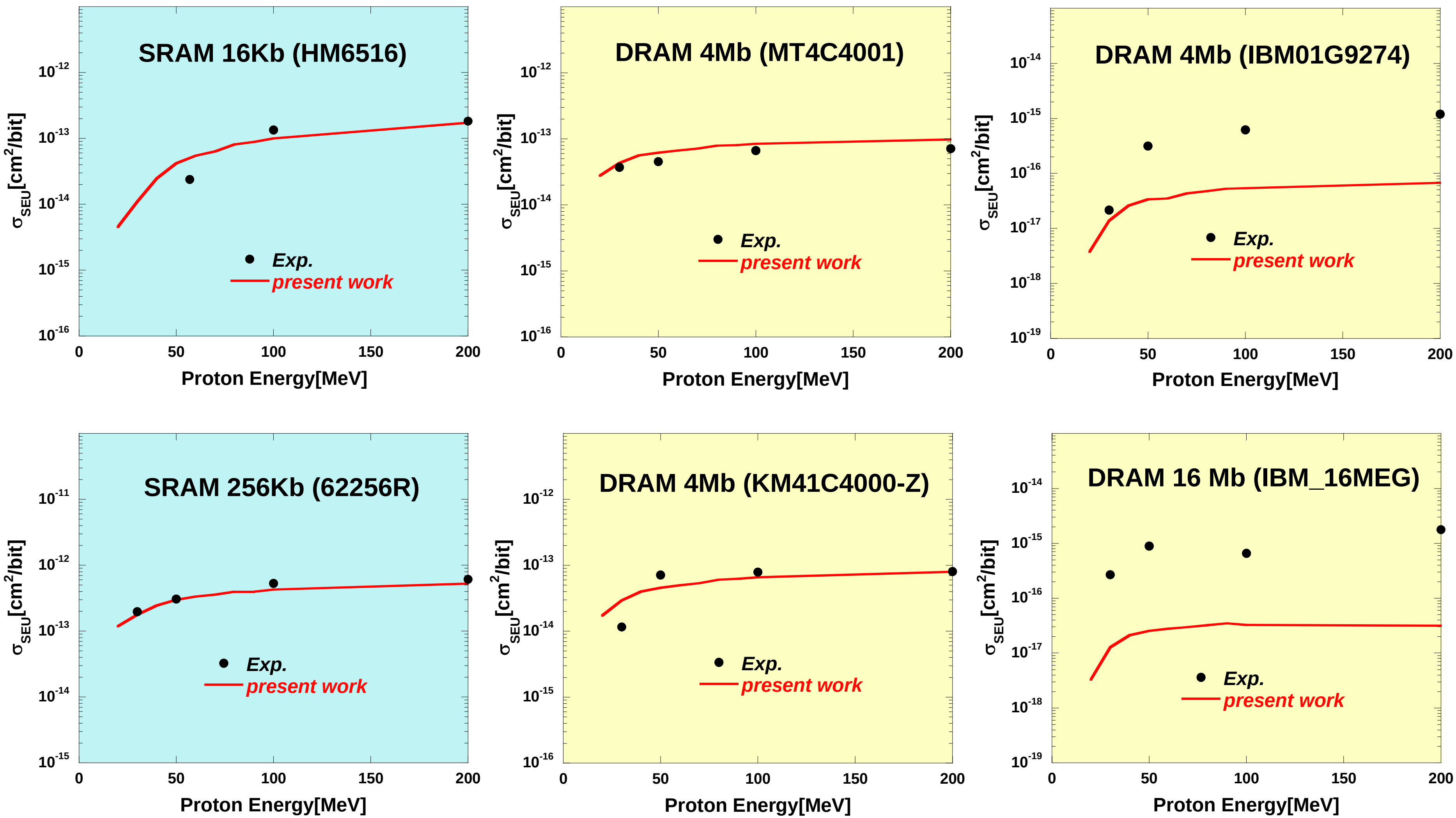




Ref.) P.D. Bradley and E. Normand, IEEE NS Vol. 45, No.6 pp. 2929-2940 (1998)

Comparison with experimental data (II)

Sensitive depth = 2 μm



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

Discussion

(a) Difference in **n-SEU and p-SEU**

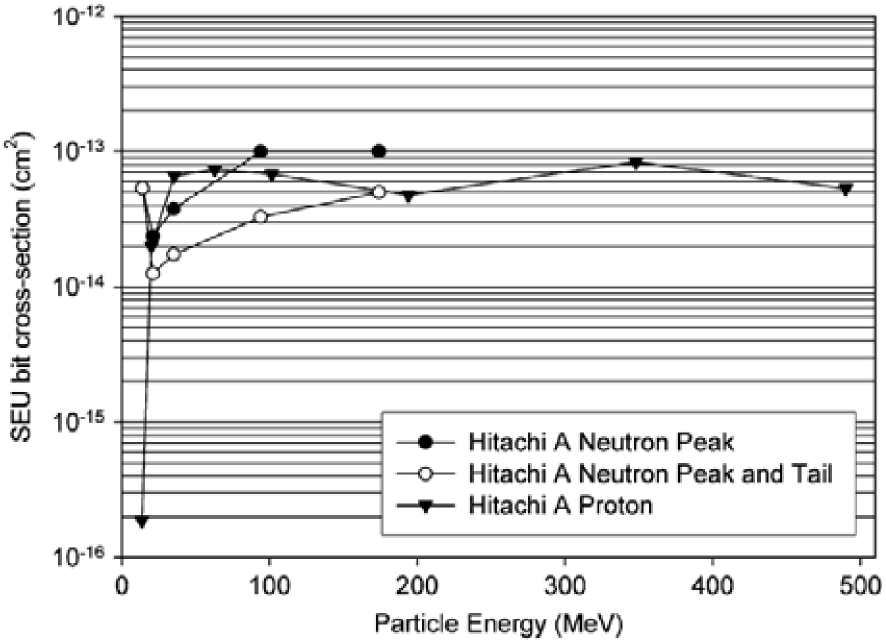
(b) Effect of **elastic scattering** on SEU

(c) **Incident energy dependence of secondary ions** having significant contribution to SEU

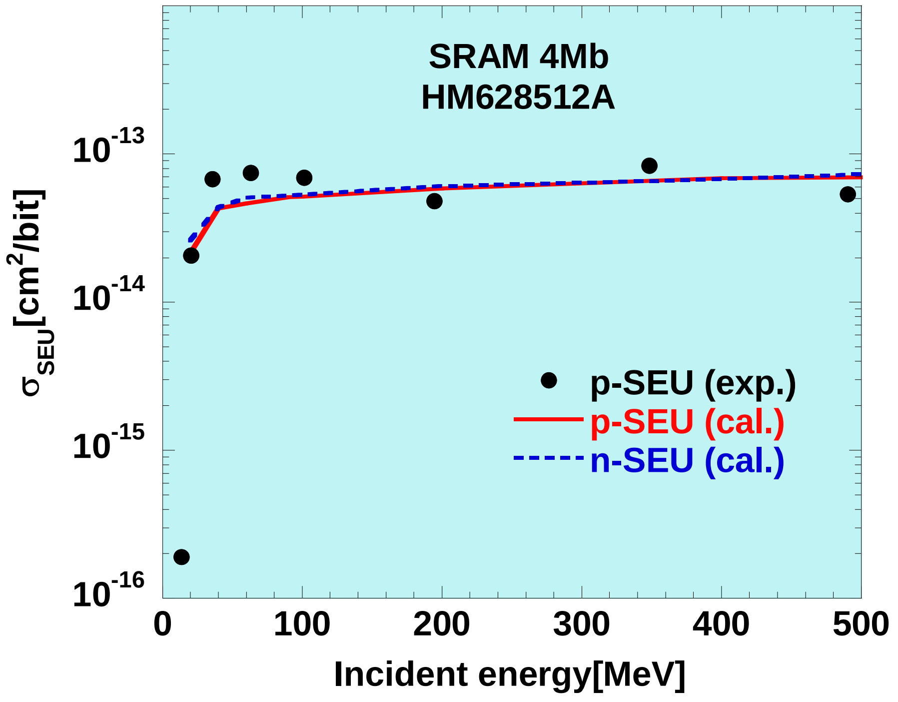
(d) Effect of **simultaneous multiple ions emission**
- *Inclusive (conventional) nuclear data vs Exclusive (event-by-event)* -

(a) n-SEU and p-SEU

4Mb SRAM, 0.5 μm (HM628512ALP-7)

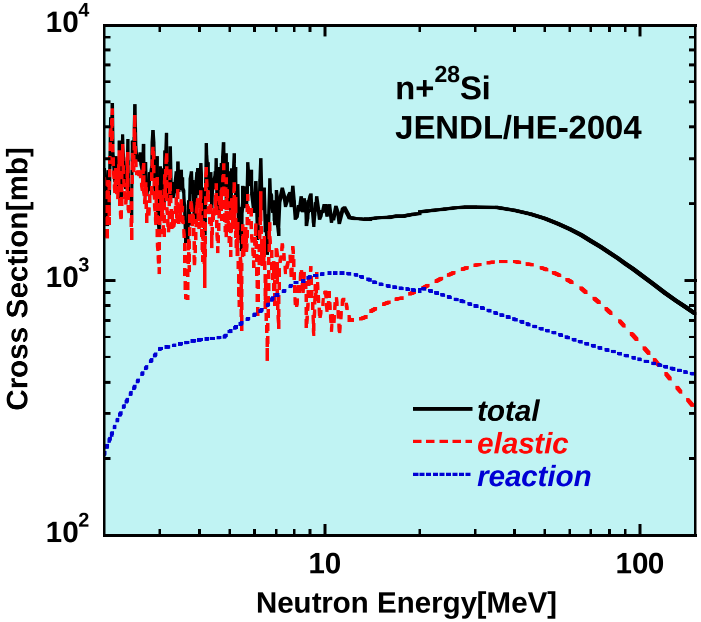


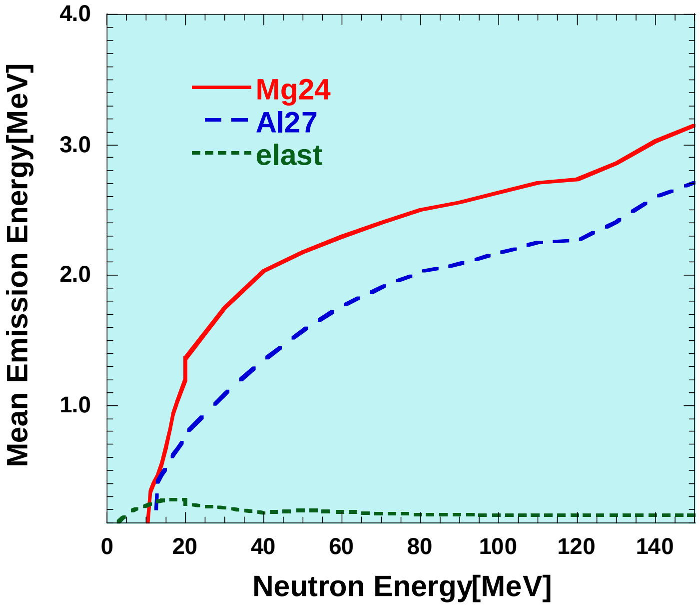
Sensitive depth = 2 μm



Ref.) C.S. Dyer et al., IEEE NS Vol.51, No.5, 2817 (2004)

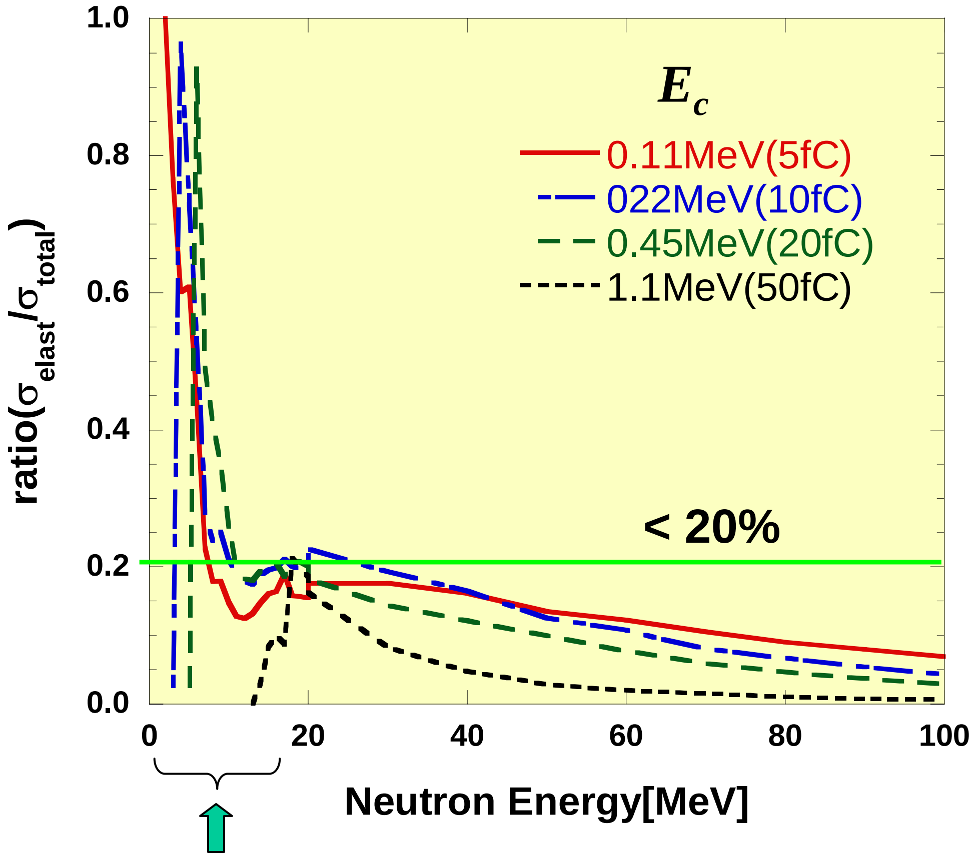
(b) Effect of elastic scattering





Sensitive volume: $1 \times 1 \times 1\ \mu m^3$

$$h(E_d) = \Theta(E_d - E_c)$$



Threshold energy region for SEU < 20 MeV

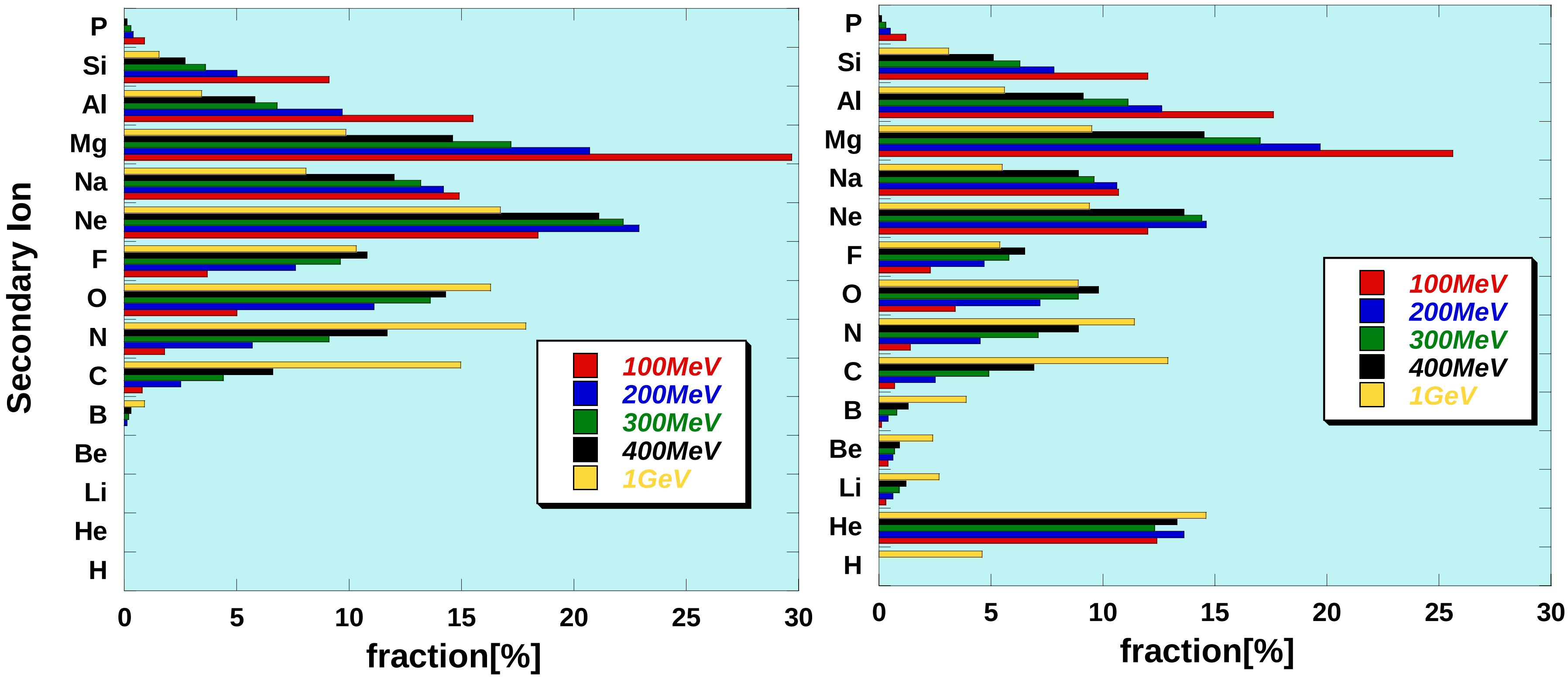
(c) Incident energy dependence of secondary ions having significant contribution to SEU

p-SEU Cubic geometry: L_g=10 μm (interaction region)

$$h(E_d) = \Theta(E_d - E_c)$$

L_s = 1μm (sensitive region)

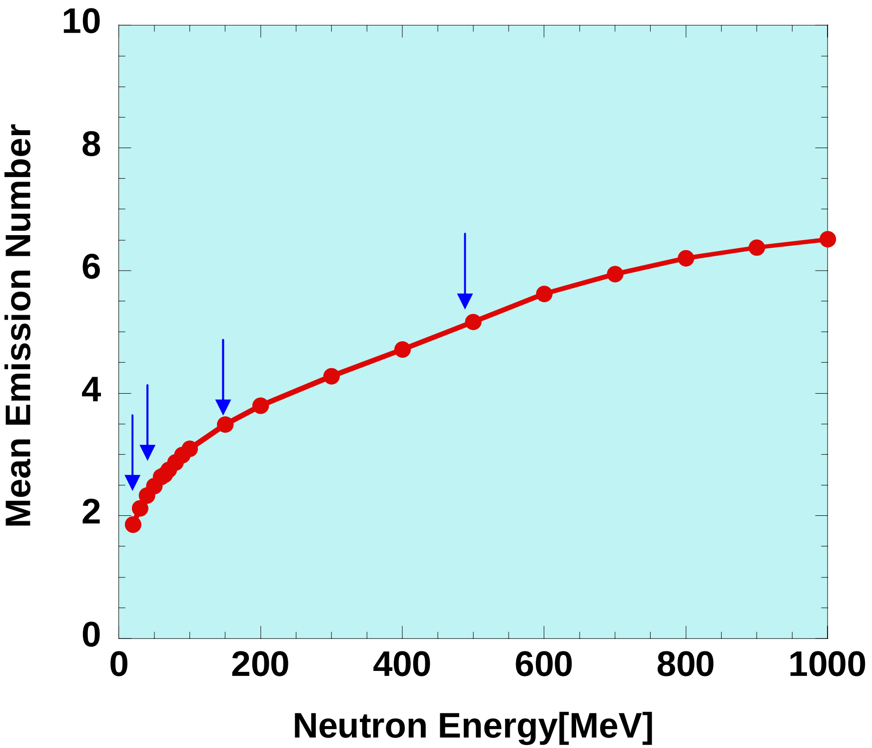
(1) Q_c= 50 fC (1.1 MeV) **(2) Q_c= 10 fC (0.22 MeV)**



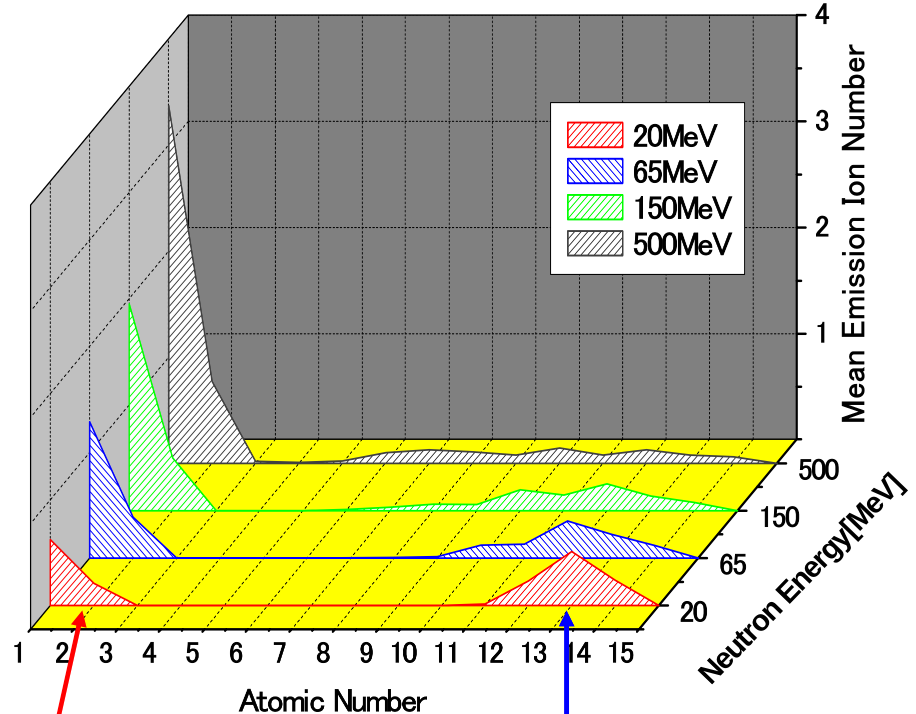
(d) Effect of simultaneous multiple ions emission

JQMD/GEM calculation for n + ^{28}Si reaction

Mean number of secondary ions



Dependence of atomic number



Low LET ions

High LET ions (~ 1)

Inclusive data vs Exclusive data

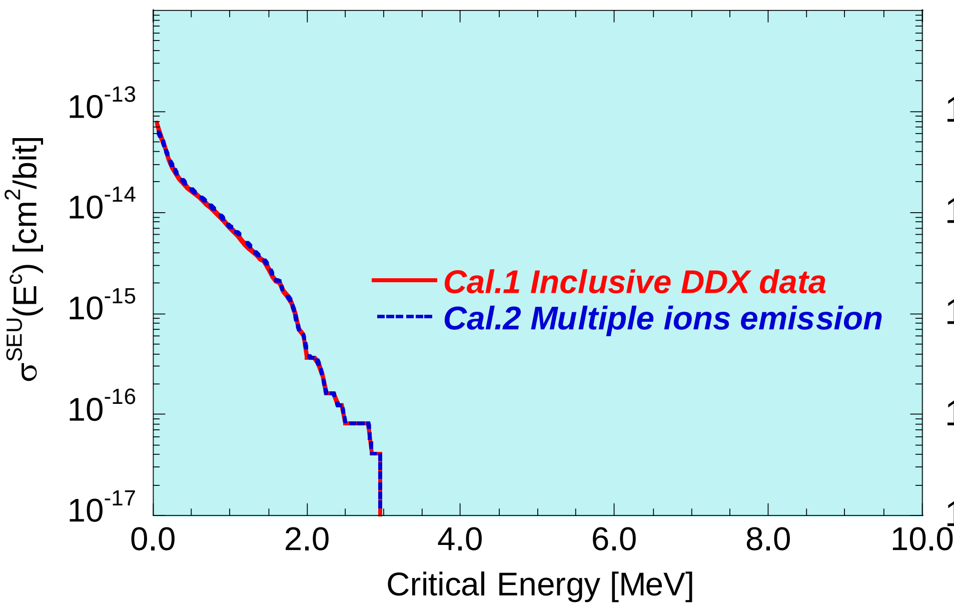
SEU cross sections as a function of critical energy E_c

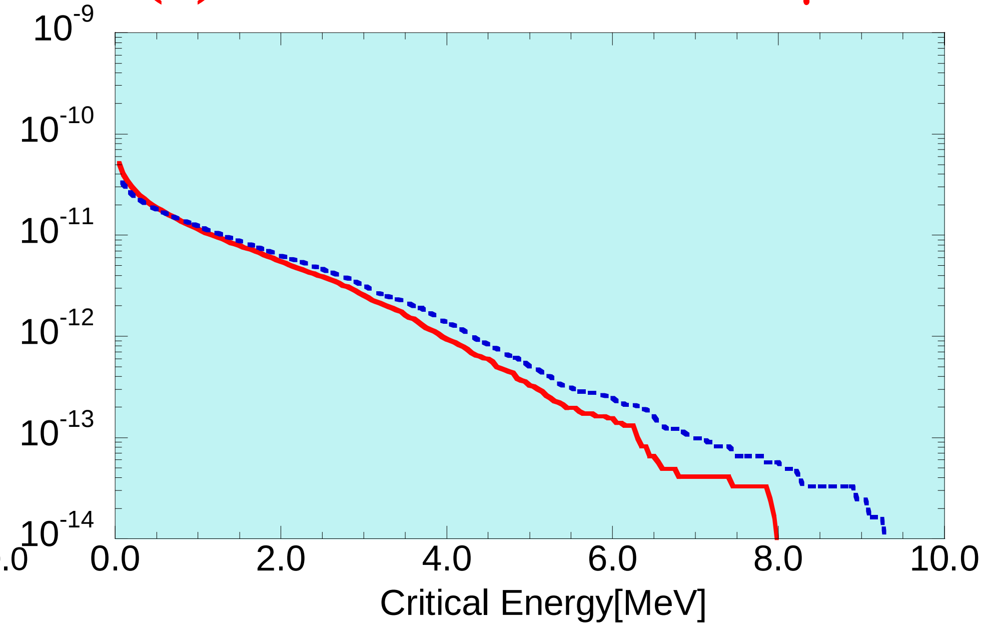
$$h(E_d) = \Theta(E_d - E_c)$$

$$\sigma_{SEU}(E_n, E_c) = \int \sigma_{ED}(E_n, E_d, SV) \cdot h(E_d) dE_d = \int_{E_c}^{\infty} \sigma_{ED}(E_n, E_d, SV) dE_d$$

E_n = 150 MeV

(1) SV= 1.0 × 1.0 × 1.0 μm³ (2) SV=20.0 × 20.0 × 1.0 μm³

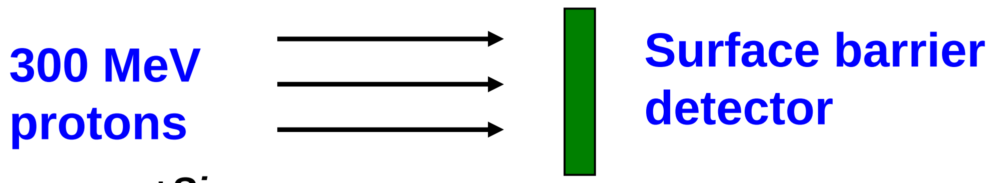


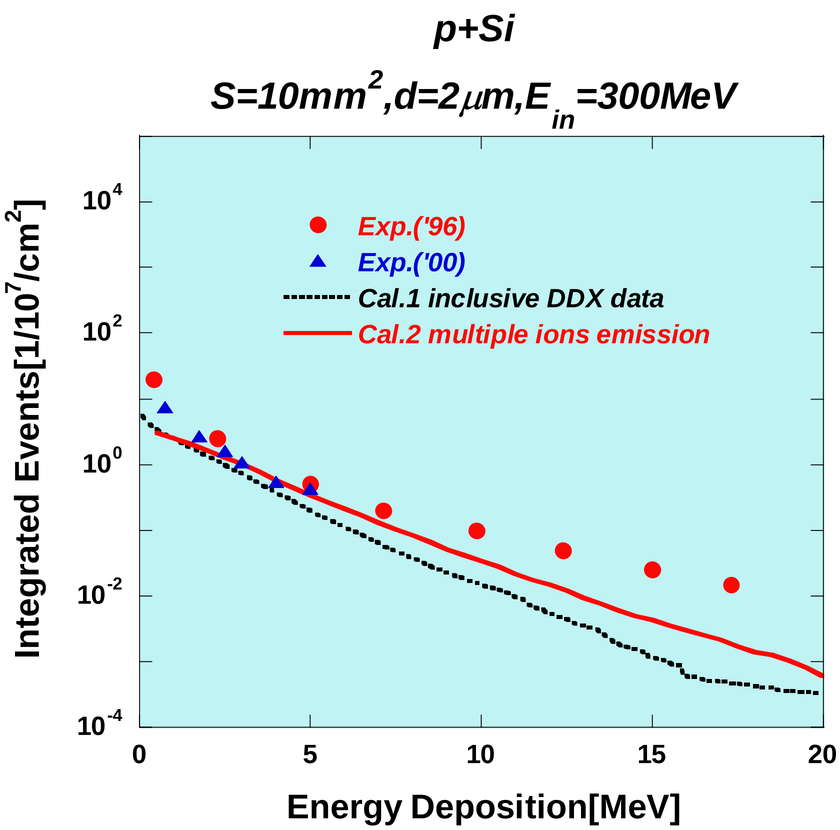


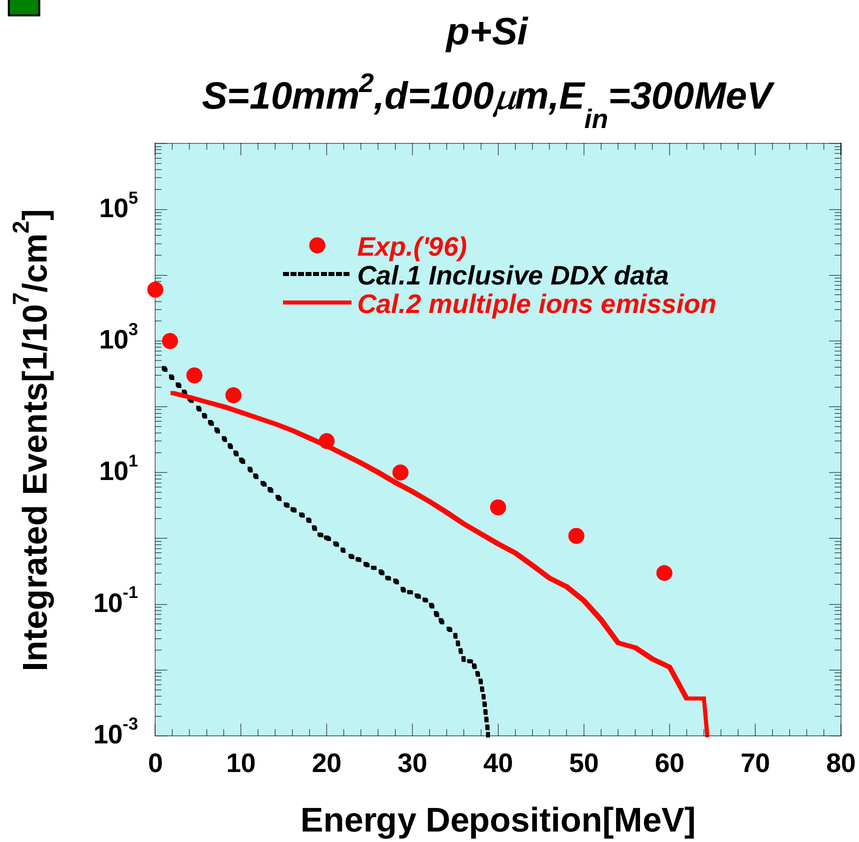
Q_c [fC] = 44.4 * E_c [MeV]

Energy deposition spectrum of Si detector

(Inclusive DDX data .vs. Multiple ions emission)







Exp.data : J. Barak et al., IEEE Trans. on Nucl. Sci. **43**, No.3 (1996) p.979; *ibid.*, **47**. No.3 (2000), p.545.

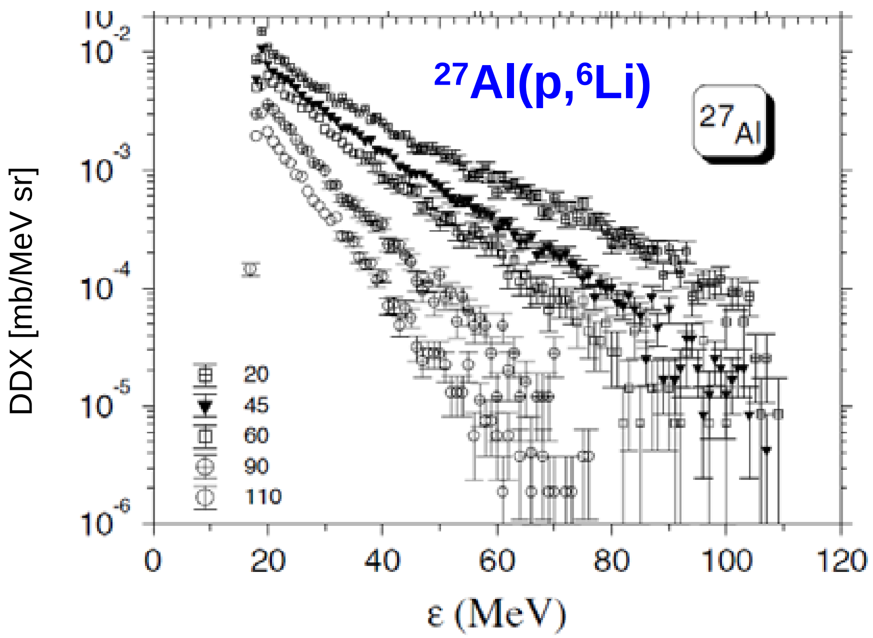
Summary

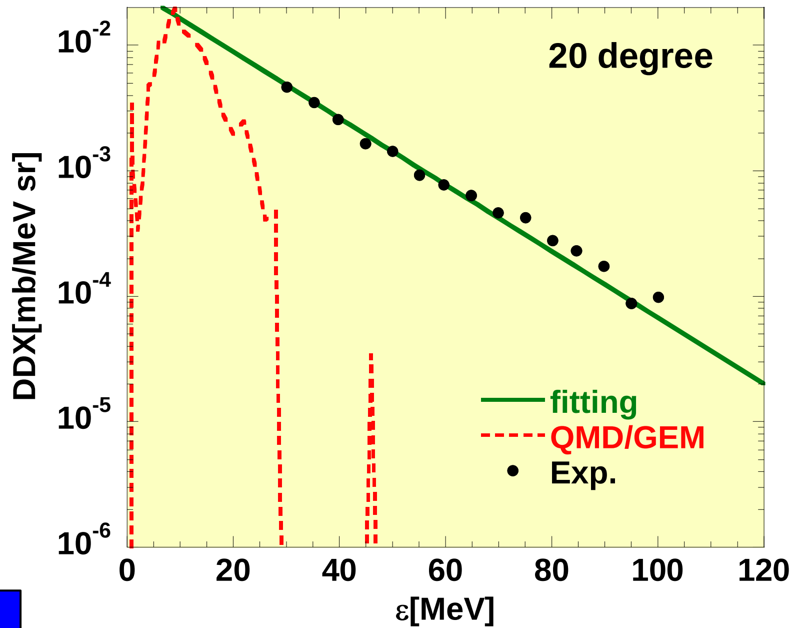
- Overview of nucleon-induced single-event upset phenomena
- Calculation of SEU cross sections using the semi-empirical model based on the sensitive volume concept
- Influences of the nuclear data on SEU simulation:
  (a) n-SEU vs p-SEU
  (b) elastic scattering
  (c) secondary reaction products
  (d) multiple ions emission : inclusive vs exclusive

Future : 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.

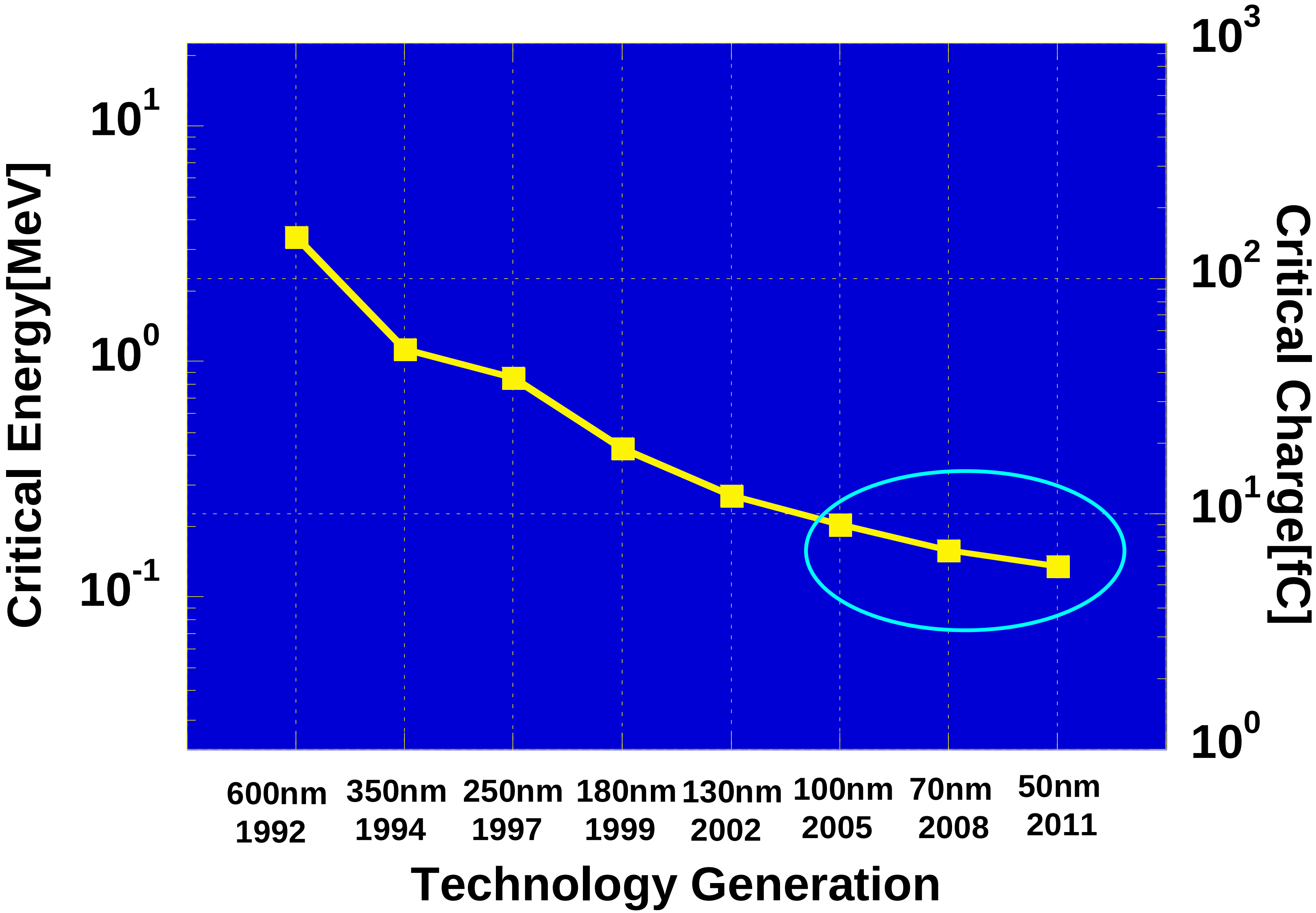
H. Machner et al., PRC 73, 044606 (2006): He, Li, Be, B from 200 MeV p+Al





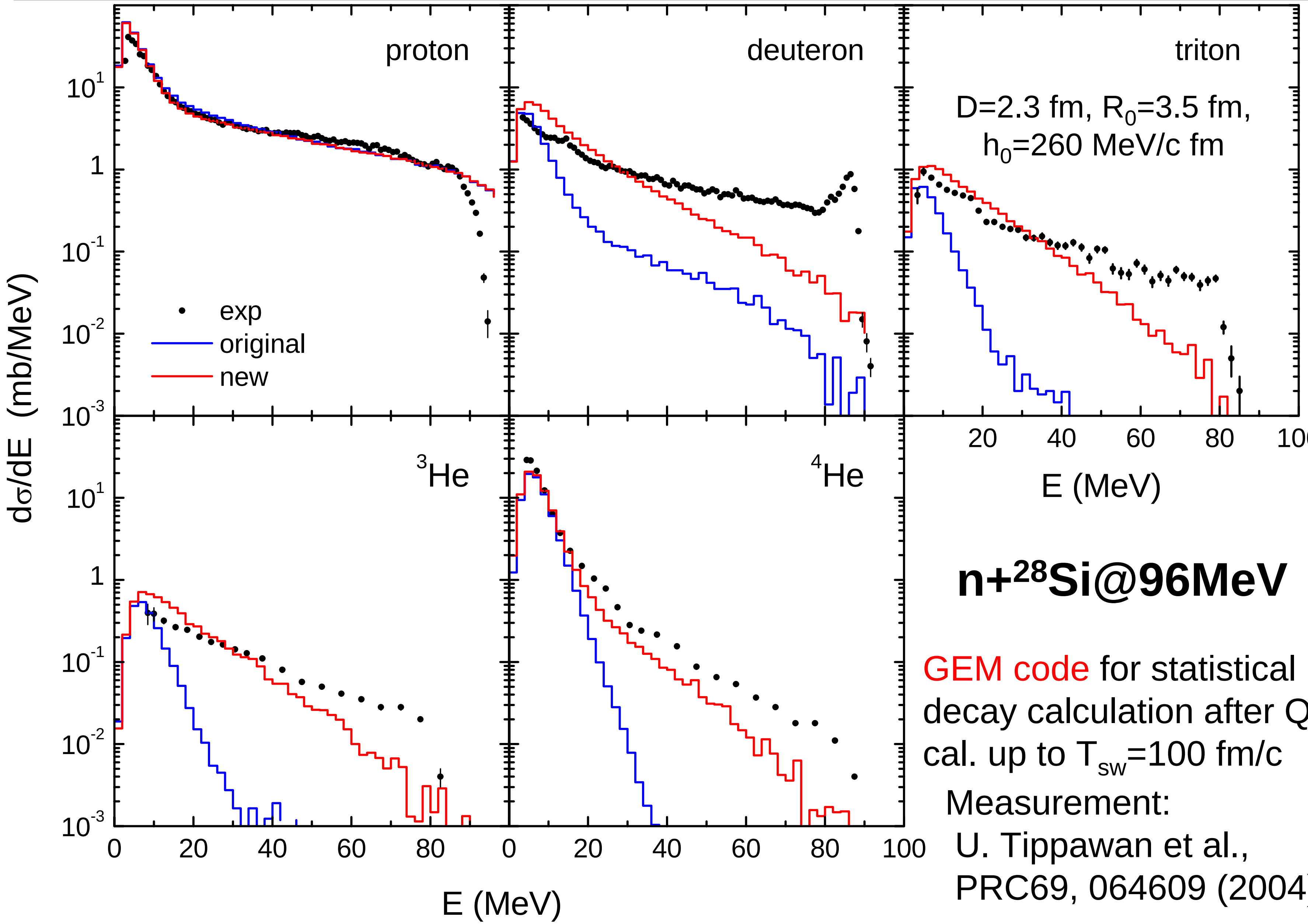
Proposal of a new experiment using the inverse kinematics @RIBF, RIKEN → ^{28}Si(^{1}H,X)

Critical charge for SRAM



P. Shivakumar et al., Int. Conf. on Dependable Systems and Networks, IEEE Proc. (2002).

Improvement of QMD calculation



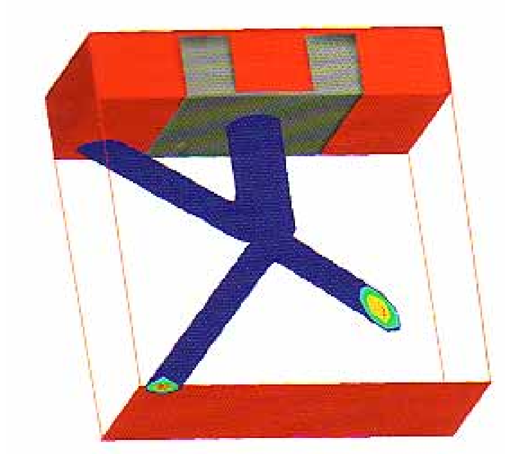
n+^{28}Si@96MeV

GEM code for statistical decay calculation after QMD cal. up to T_{sw}=100 fm/c

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

Future : energy-deposition process

Spatial distribution of initially-deposited charges

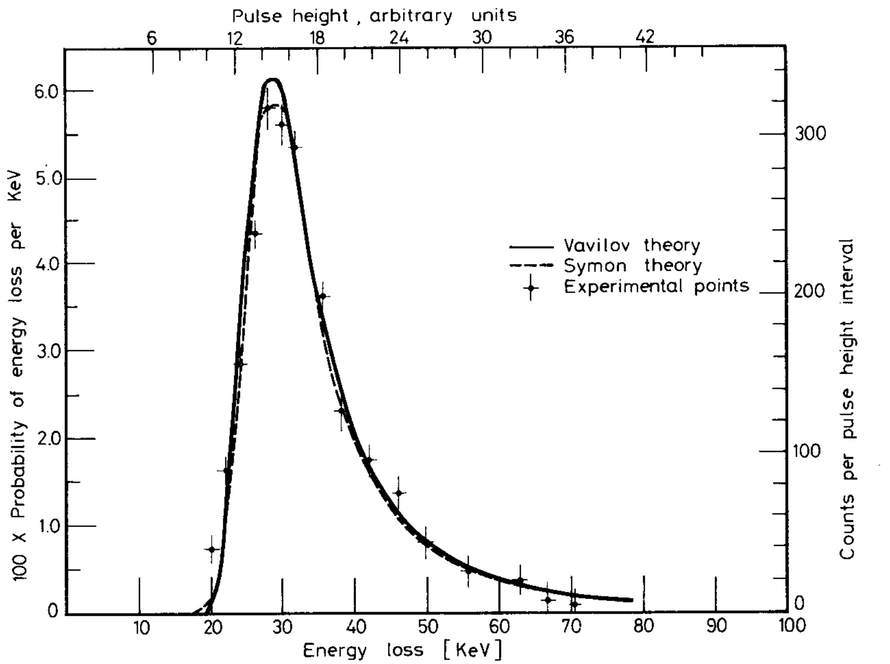


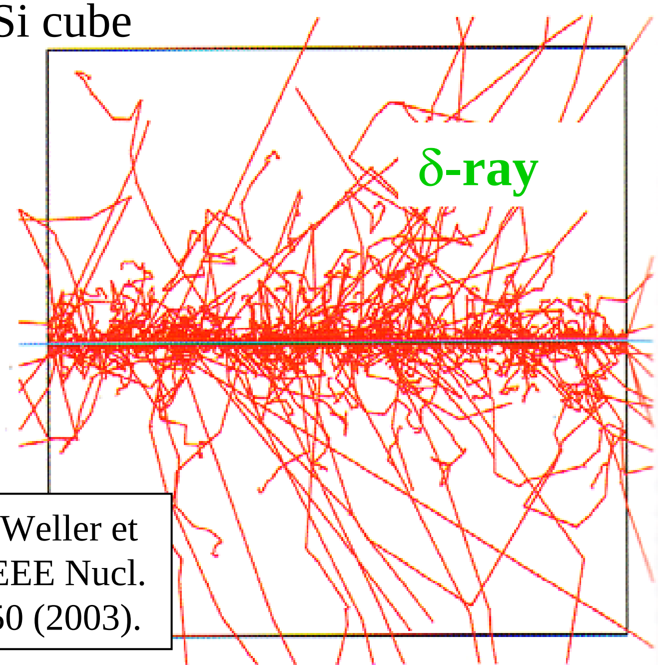
Energy straggling

track structure effect

100MeV proton

1μm Si cube





R.A. Weller et al., IEEE Nucl. Sci. 50 (2003).