Monte-Carlo Simulation for the Effects of Composite Materials on Single Event Effects of Sub-100 nm Semi-conductor Devices

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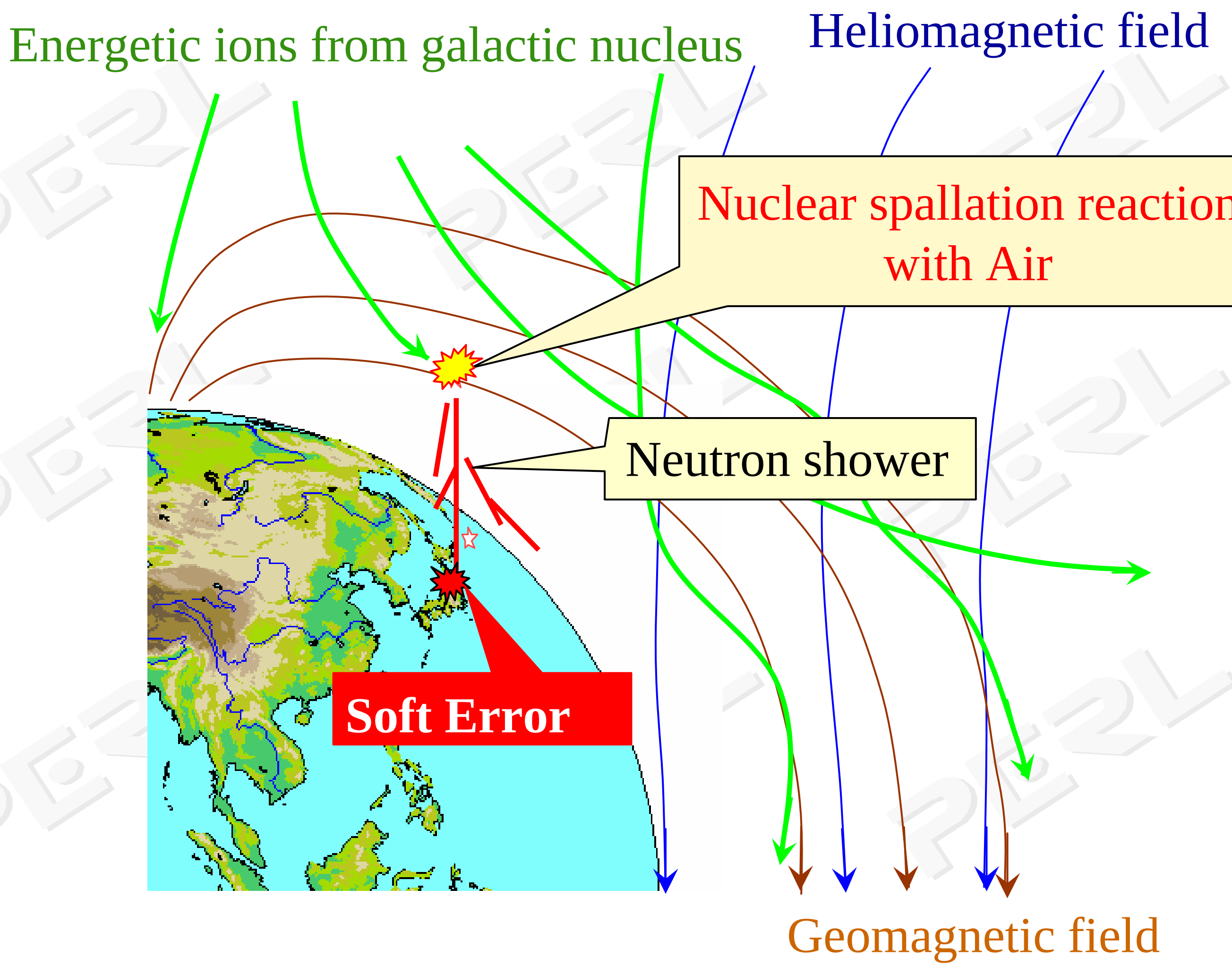
Outline

- What is neutron SEE[1] at the ground?
- Nuclear spallation model in MONTE-CARLO Simulation code CORIMS[2](Si only model) and its validation with nuclear reaction data.
- Semiconductor device model and its validation with device error data (Accelerator/Field).
- Recent progress : Simulation of soft-error in composite materials (SEALER[3])
- Proposal for co-operative linkage with nuclear scienc

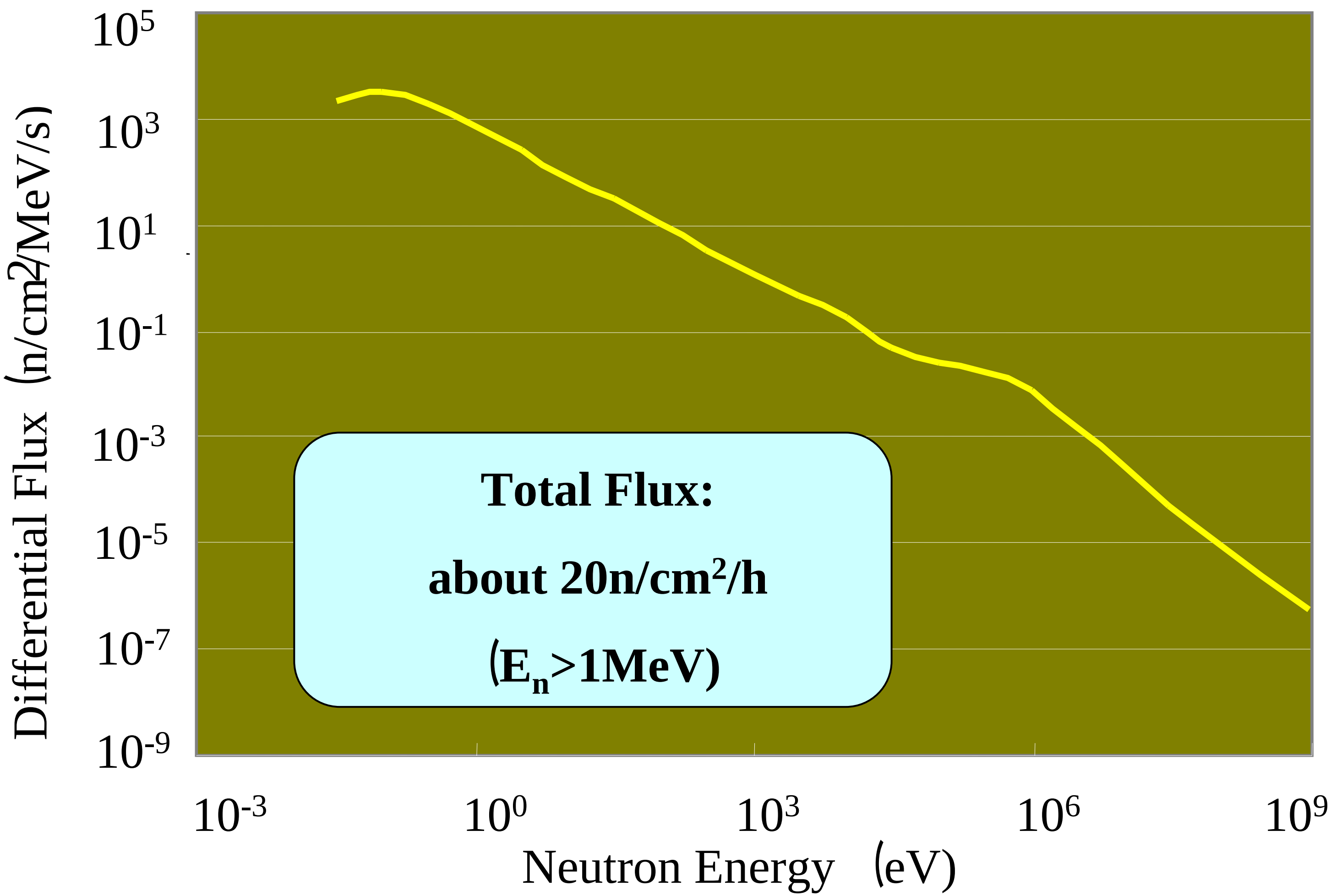
1:Single Event Effect: Phenomena in single hit of neutron; both soft and hard (destructive) error are included

2:Cosmic Ray Impact Simulator 3:Single Event Adverse and Local Effects Reliever

Macroscopic Mechanism of Terrestrial Neutron Soft-Error

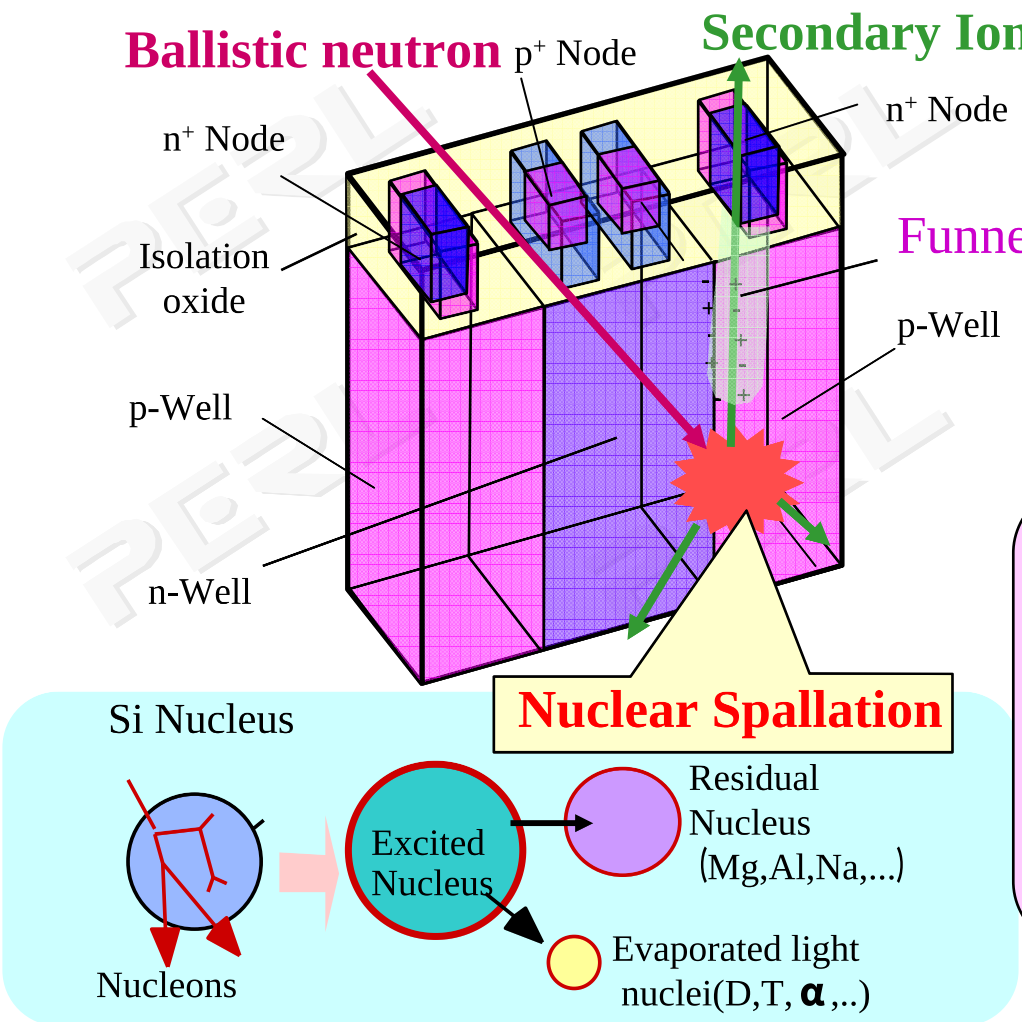


Estimated Neutron Spectrum in Tokyo*



*Estimated from the spectrum in NewYork (F. Ziegler, *IBM J. Res. Develop.*, vol.40, No.1, pp. 19-39(1996)

Microscopic Mechanism of Soft-Error in SRAM[1]

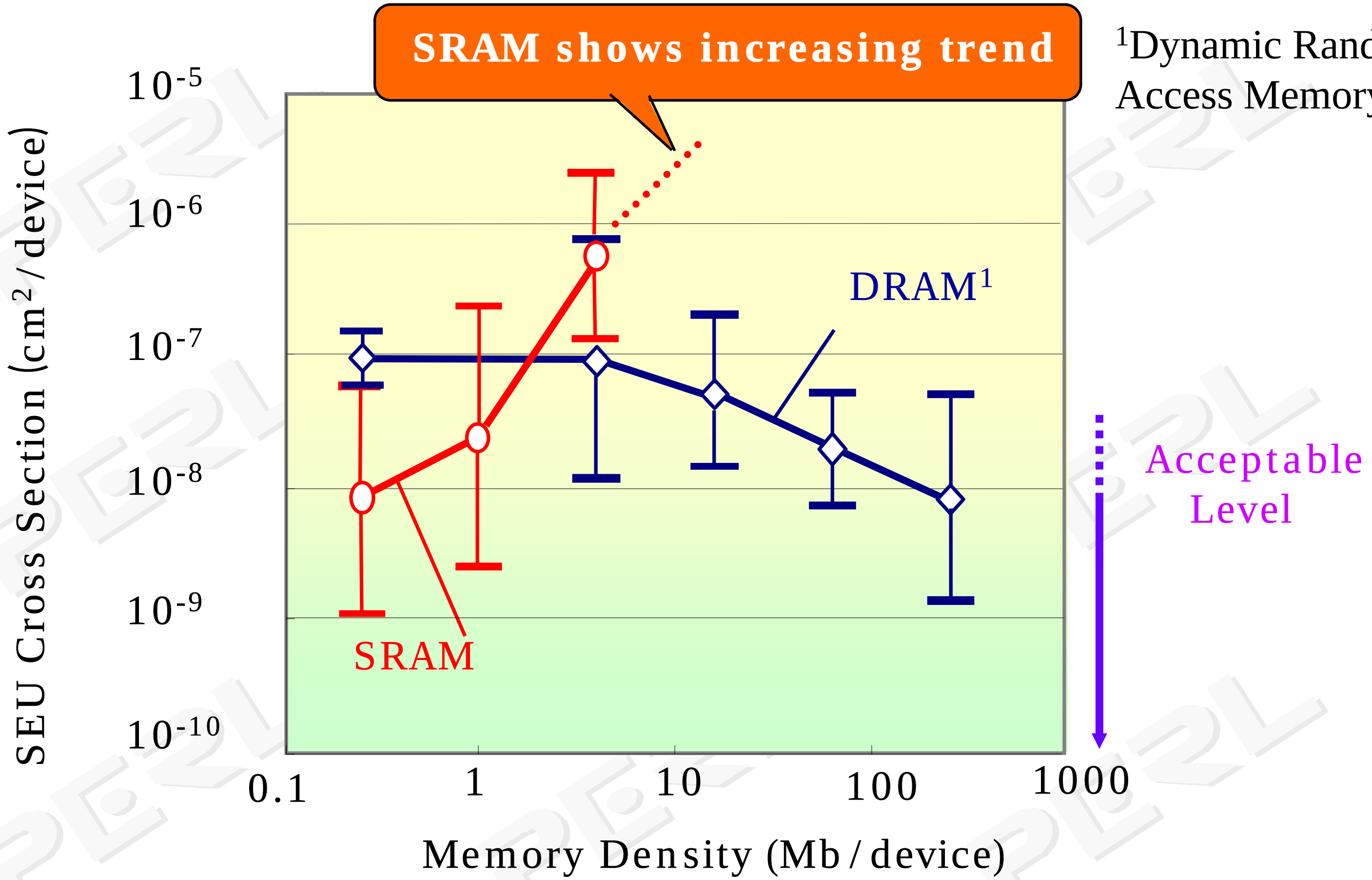


Charge collection to node

Soft-error (flip of stored data) takes place when:
Q_{col} (charge collected) >Q_{crit} (Threshold charge of “1” or “0”)

[1]Static Random Access Memory

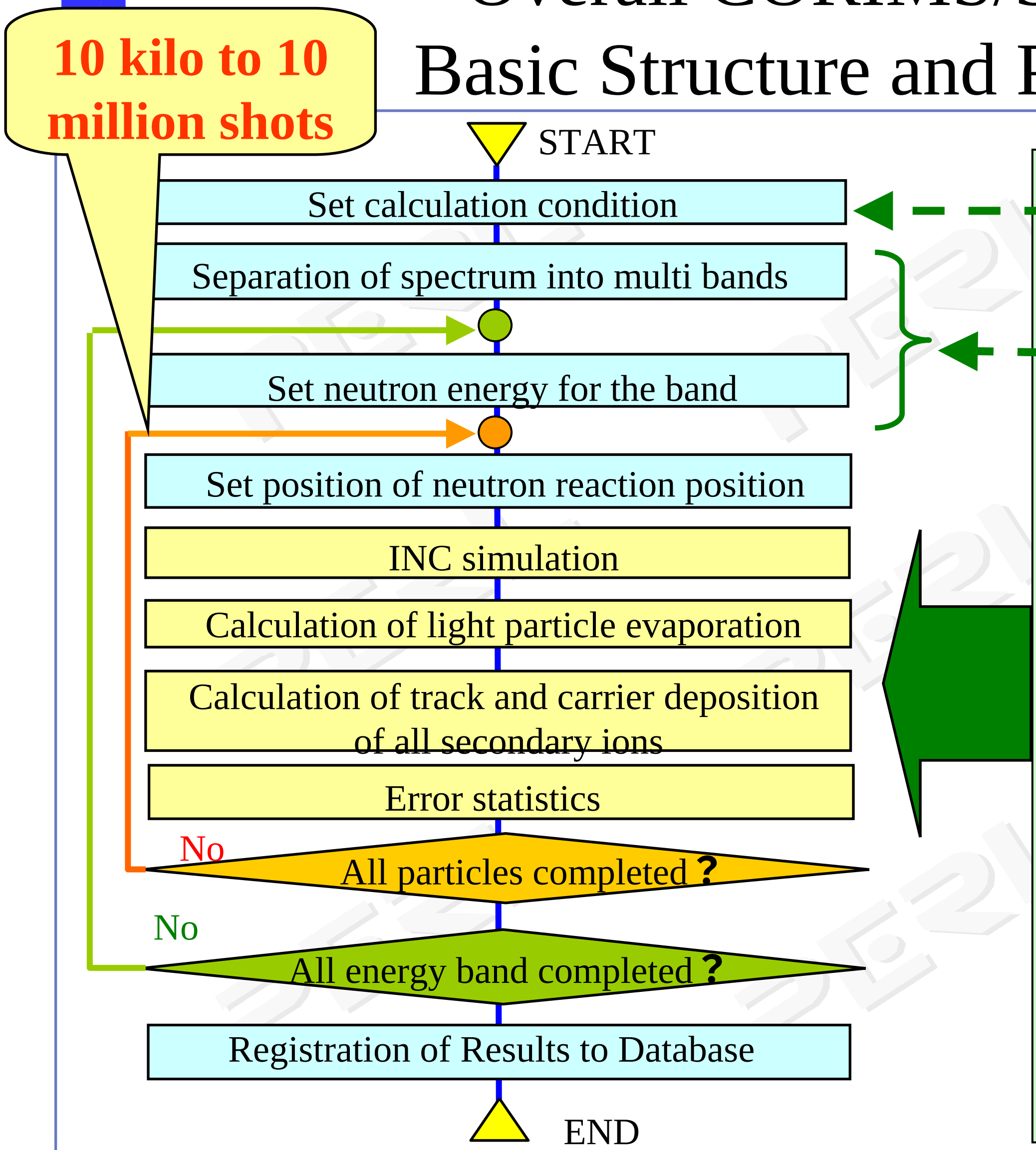
Current General Trends Retrieved from Literatures



[1]Dynamic Random Access Memory

*SEU Cross Section = Errors/number of incident nucleon

Overall CORIMS/SEALER Basic Structure and Procedures



Database

- Properties of substrate materials

  (Si, SiO_2,Si_3N_4.TiN, Cu, Al, WSi_2, Ta_2O_5)
- Neutron spectrum

  (Accelerators / terrestrial neutron)
- Nuclear total/reaction cross section

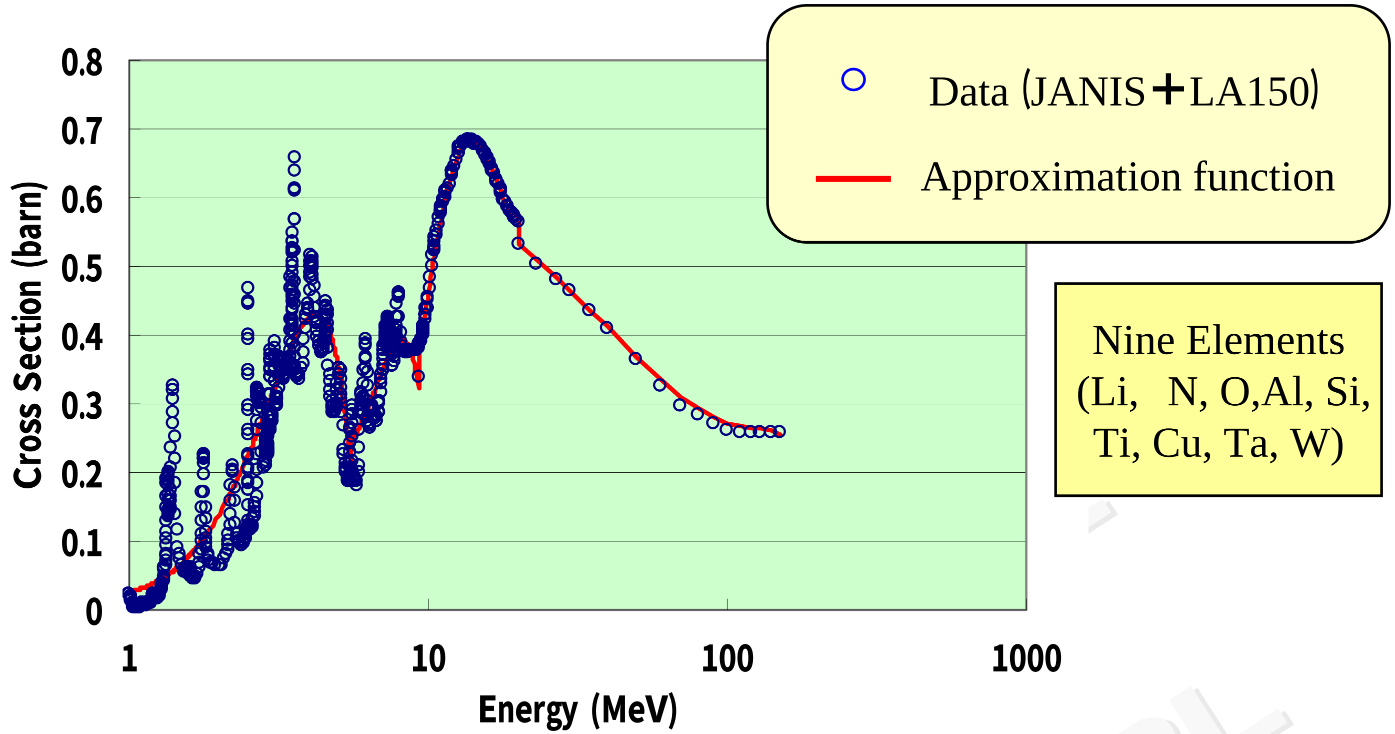
  (from JENDL 3.3, JANIS 2.0, LA150)
- Nucleon-nucleon scattering cross section (with non-isotropic force)
- Properties of secondary ions
- Inverse reaction cross section (GEM)
- LET of secondary ions as a function of energy in all material
- Device design parameters

Physical Model Developments from CORIMS to SEALER

Code Name	CORIMS (Former)	SEALER (present)
Spallation target nuclei	Si only	N,O,Al,Si,Ti,Cu,W
Secondary ions	About *100* isotopes from Si spallation	More than ***2000*** isotopes from the elements above
LET[1] calculation	*14* elements (5 isotopes) in Si substrate *only*	***78*** elements in ***8*** composite materials (Si,SiO_2,Si_3N_4,WSi_2,Cu,Al,Ta_2O_5)
Spallation Model	Intra-Nuclear-Cascade (INC), Statistical evaporation model with *tabulated inverse reaction cross section*	Same but with *Generalized Evaporation Model (**GEM**[2])*

1: Linear Energy Transfer、2:Generalized Evaporation Model

Total Reaction Cross Section and Example of Approximation Function (Nitrogen-14)

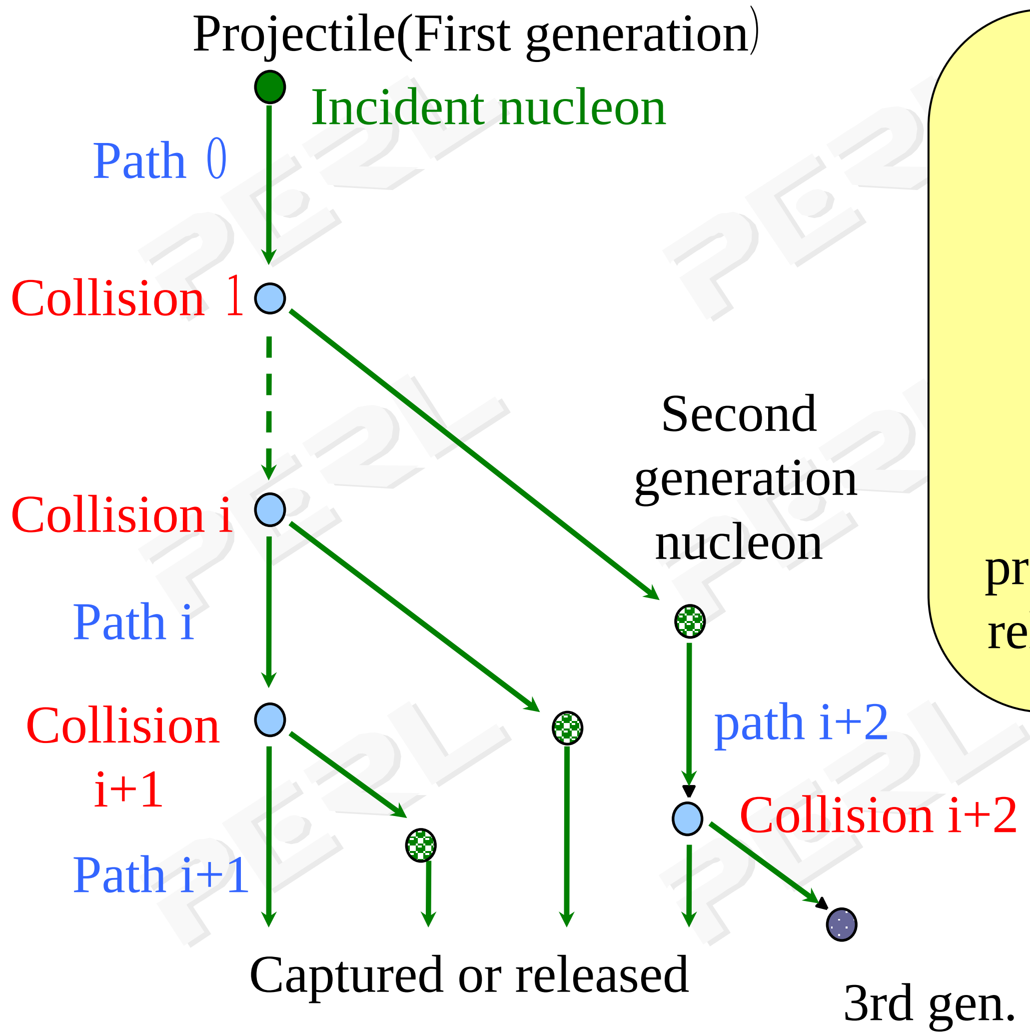


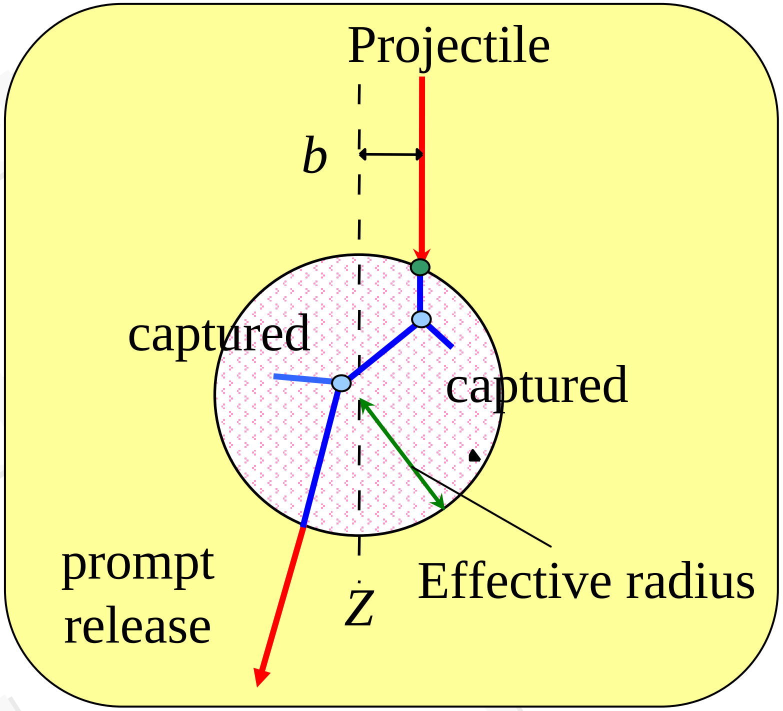
Nine Elements (Li, N, O, Al, Si, Ti, Cu, Ta, W)

$$\sigma_{nonela} = \begin{cases} -0.0202\times E_n^3 + 0.15144\times E_n^2 - 0.1999\times E_n + 0.095 & (0 \le E_n < 5.53) \\ -0.0092\times E_n^3 + 0.1799\times E_n^2 - 1.0975\times E_n + 2.369 & (5.53 \le E_n < 9.352) \\ 0.001133\times E_n^3 - 0.0572\times E_n^2 + 0.9343\times E_n - 4.2959 & (9.352 \le E_n < 20) \\ -2.13\times 10^{-7}\times E_n^3 - 8.0\times 10^{-5}\times E_n^2 + 0.0102\times E_n + 0.7052 & (20 \le E_n < 150) \\ 0.256 & (150 \le E_n) \end{cases}$$

Intra-Nuclear-Cascade (INC) Model

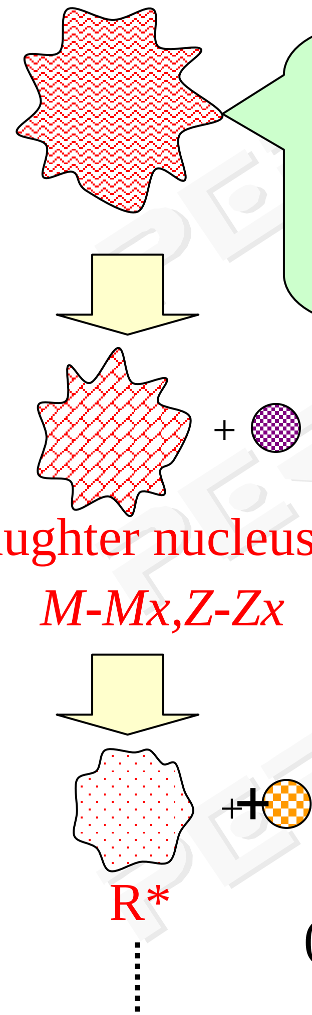
(Lexicographic processing of trees)





- Kinematic parameters of excited residual nucleus are determined after all nucleon destinations are determined

Evaporation Model of Light Particles (After Tang)



Excited residual nucleus
Mass number M
Atom number Z

+ Evaporated particle

Daughter nucleus R*
M-Mx,Z-Zx

X：M_X,Z_X,
Energy ε
(X=α,^{3}He,p,D,T,n,…)

+ Evaporated particle

R*

Y
(Y=α,^{3}He,p,D,T,n,…)

Calculation procedure

①Probability W_x for all reaction channel

$$W_X = \frac{(2S_X+1)m_X}{N_0}\int_{V_C}^{\varepsilon_{max}} d\varepsilon\varepsilon\sigma_{RX}(E_T^*;\varepsilon)\omega_R(E_R^*)$$

Inverse reaction cross section

$$\omega(E^*) = \omega_0 \exp(2\sqrt{aE^*})$$

②Set reaction channel

③Set evaporated particle kinematics

④Fix residual nucleus kinematics

Calculation of Inverse Reaction Cross Section (GEM)

$$\sigma_{inv}(\varepsilon) = \pi R_b^2 c_j \left(1 - \frac{k_j V}{\varepsilon}\right)$$

$$V = \frac{Z_j Z_d e^2}{R_c}$$

Z_d	k	k_α	c
≦20	0.51	0.81	0.0
30	0.60	0.85	-0.06
40	0.66	0.89	-0.10
≧50	0.68	0.93	-0.10

$$c_p = 1 + c$$

$$c_d = 1 + c/2$$

$$c_t = 1 + c/3$$

$$c_{^3He} = c_\alpha = 0$$

$$k_p = k$$

$$k_d = k + 0.06$$

$$k_t = k + 0.12$$

$$k_{^3He} = k_\alpha - 0.06$$

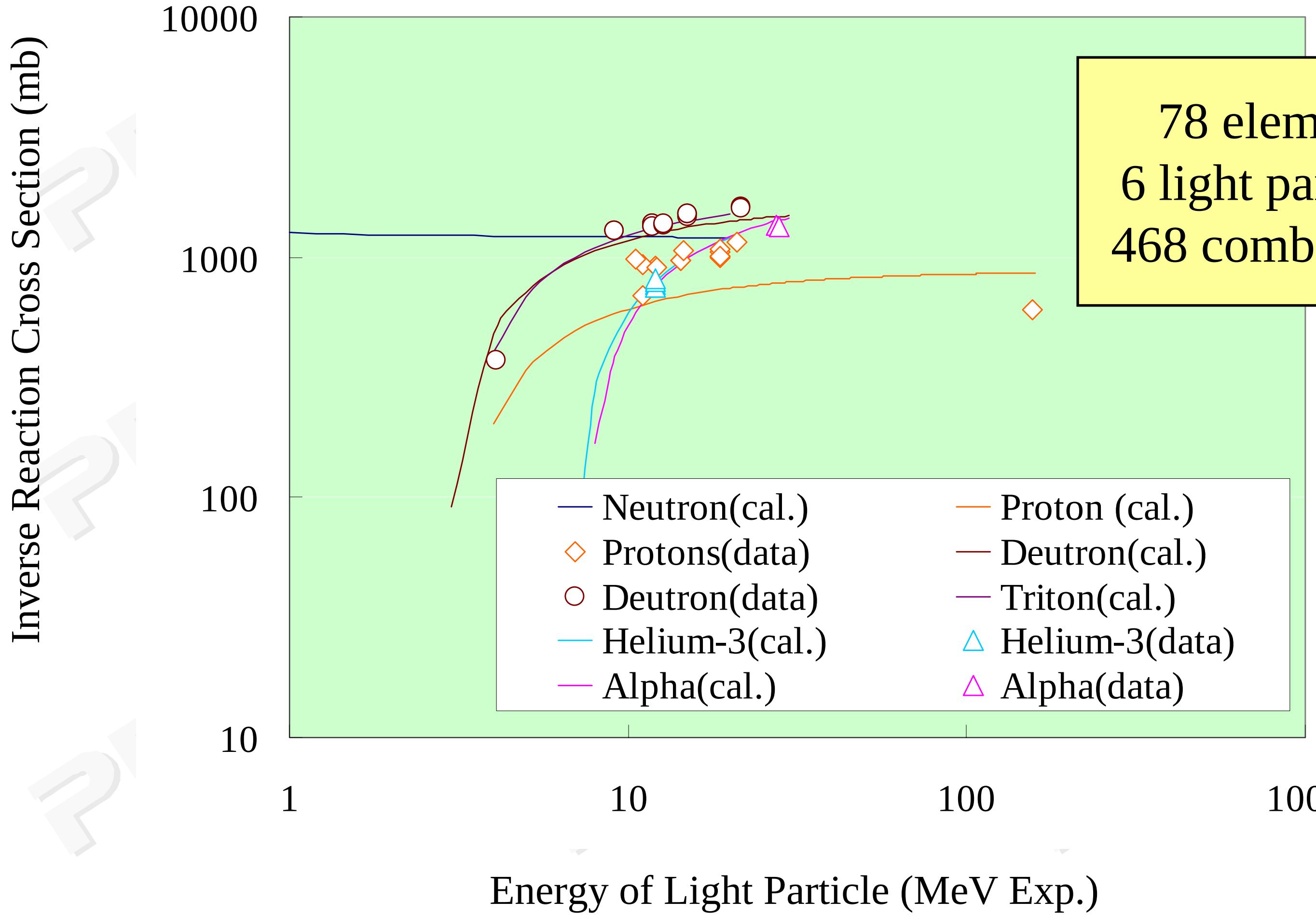
$$R_b = \begin{cases} 1.5 A_d^{1/3} & \text{(for Proton)} \\ 1.5\left(A_d^{1/3} + A_j^{1/3}\right) & \end{cases}$$

$$R_c = \begin{cases} 1.7 A_d^{1/3} & \text{(for Proton)} \\ 1.7 A_d^{1/3} + 1.2 & \end{cases}$$

*Generalized Evaporation Model, S. Furihata , Thesis for PhD. , Tohoku University(2003)

Inverse Reaction Cross Section
-Comparison of Literature Data* and GEM Calculation -

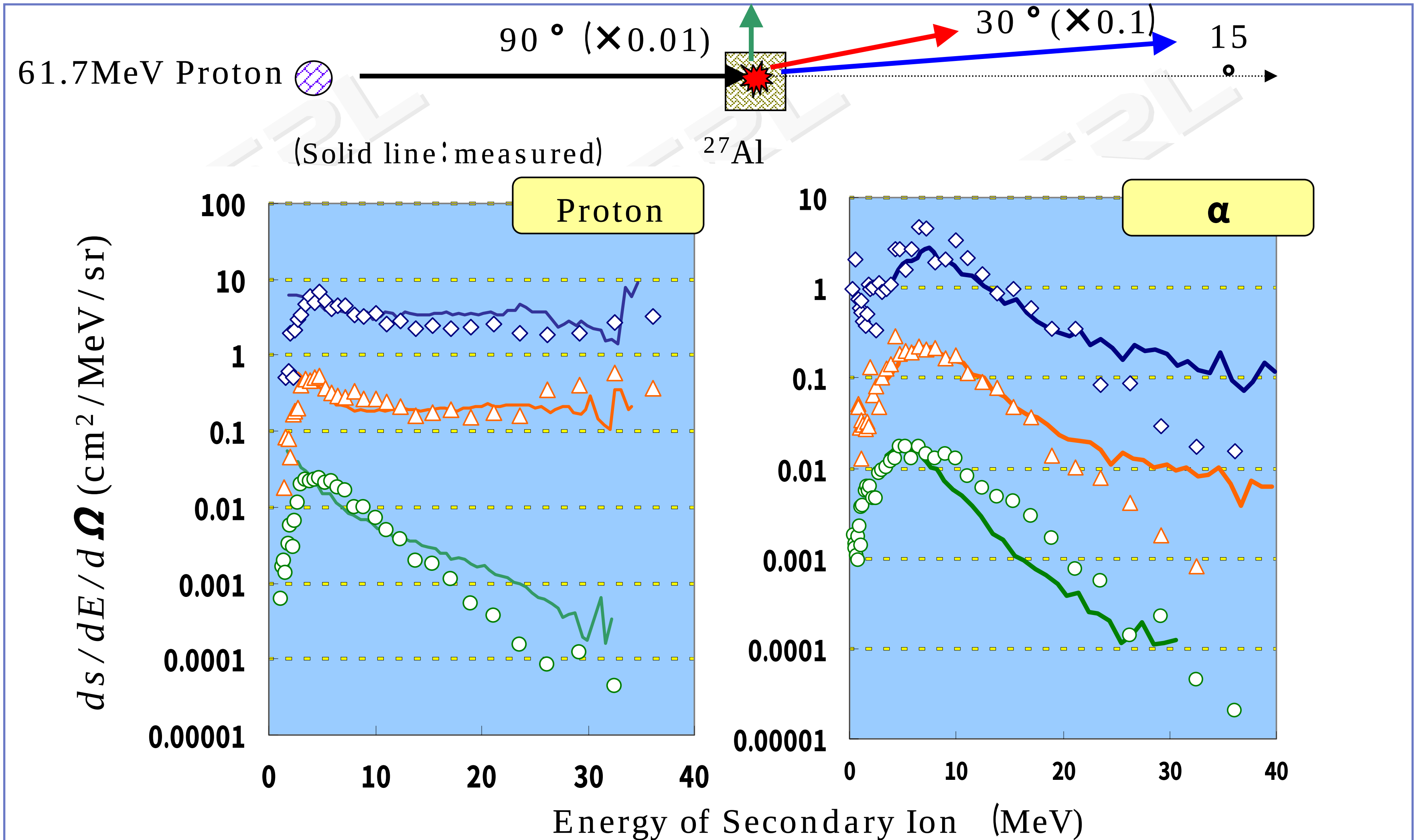
*C.M.Perley & F.G. Perley, Atomic Data and Nuclear Data Tables 17,1-101(1976)



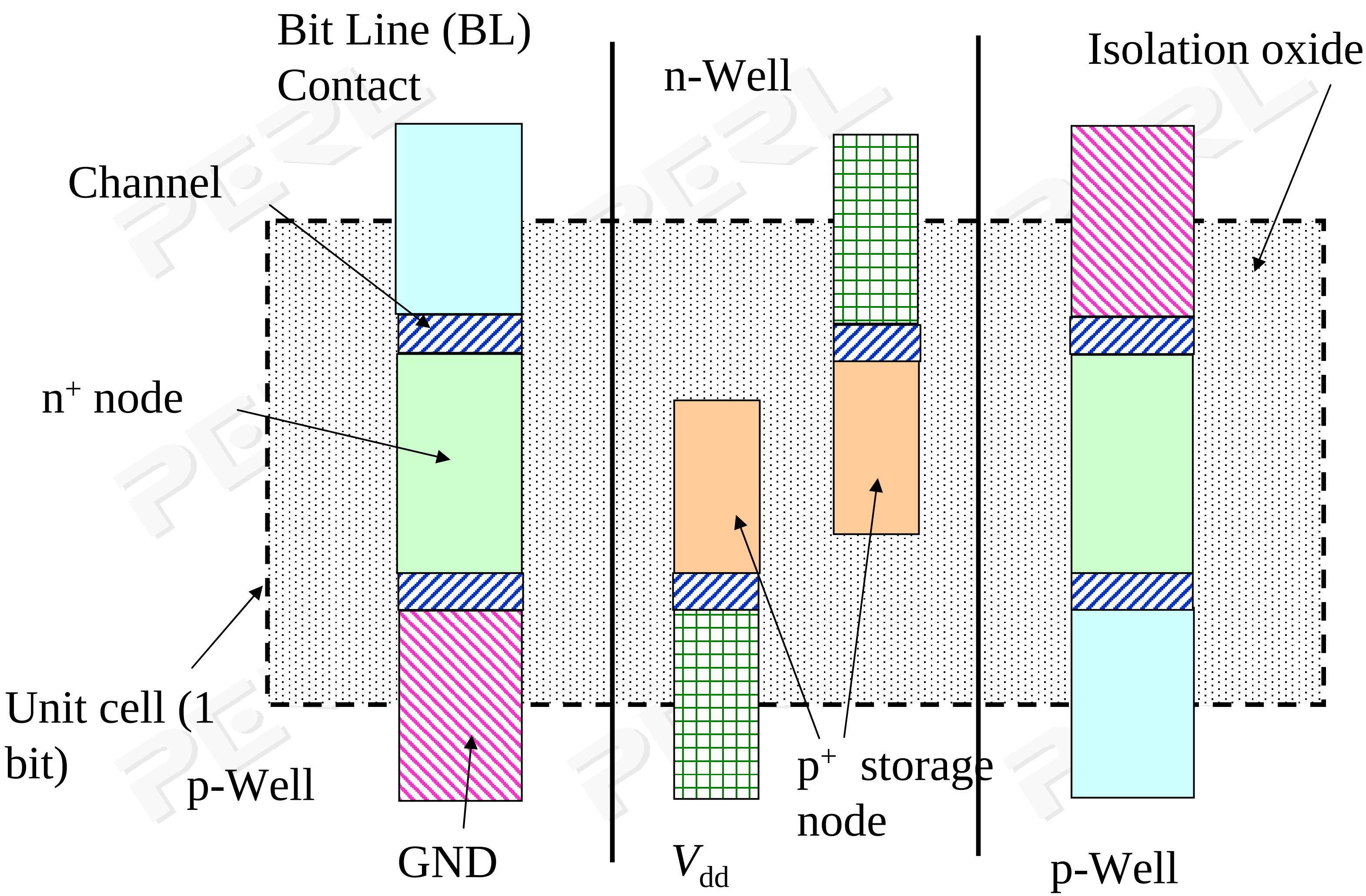
78 elements×
6 light particles=
468 combinations

Comparison between Experimental* and Simulation Results of Nuclear Spallation

*Bertland,1973



CMOS SRAM Device Layout Model



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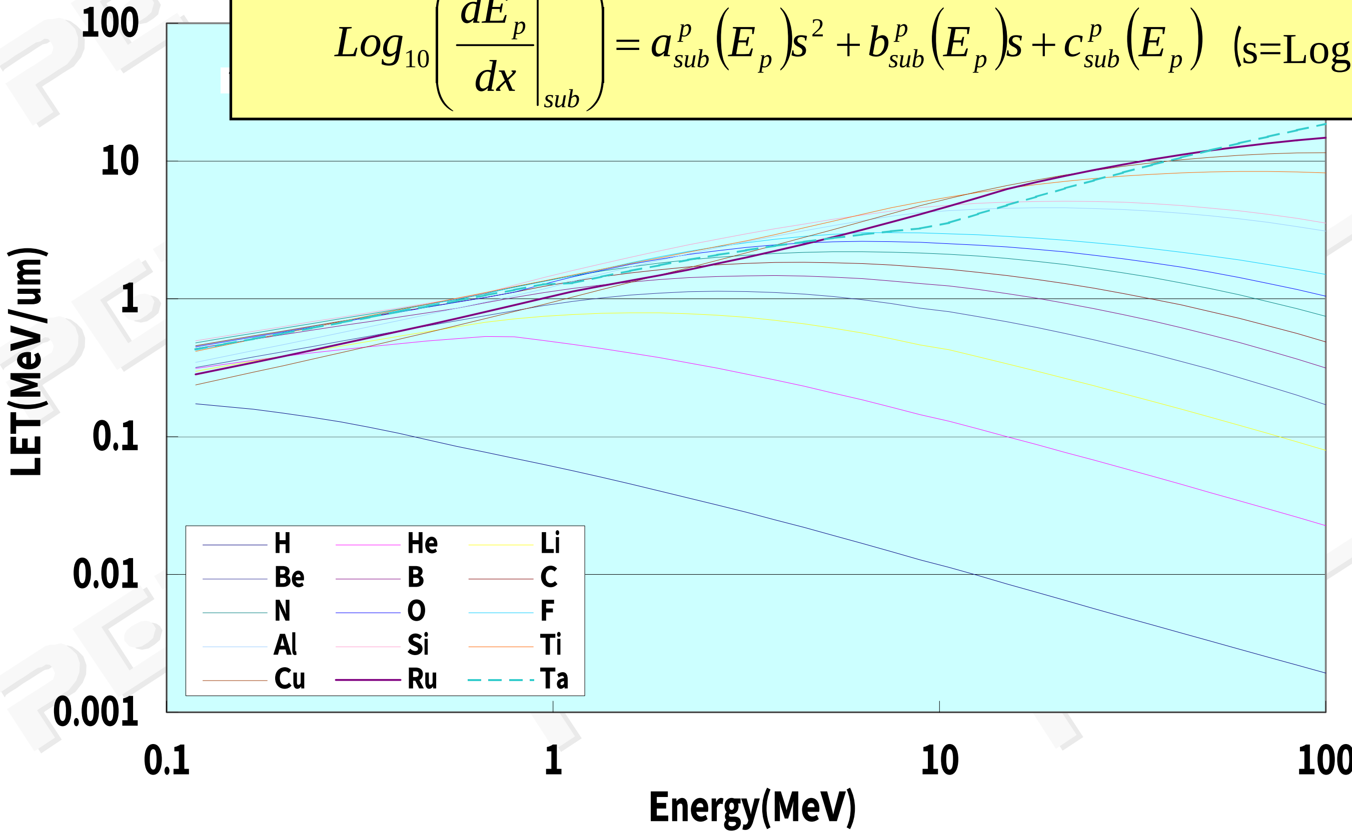
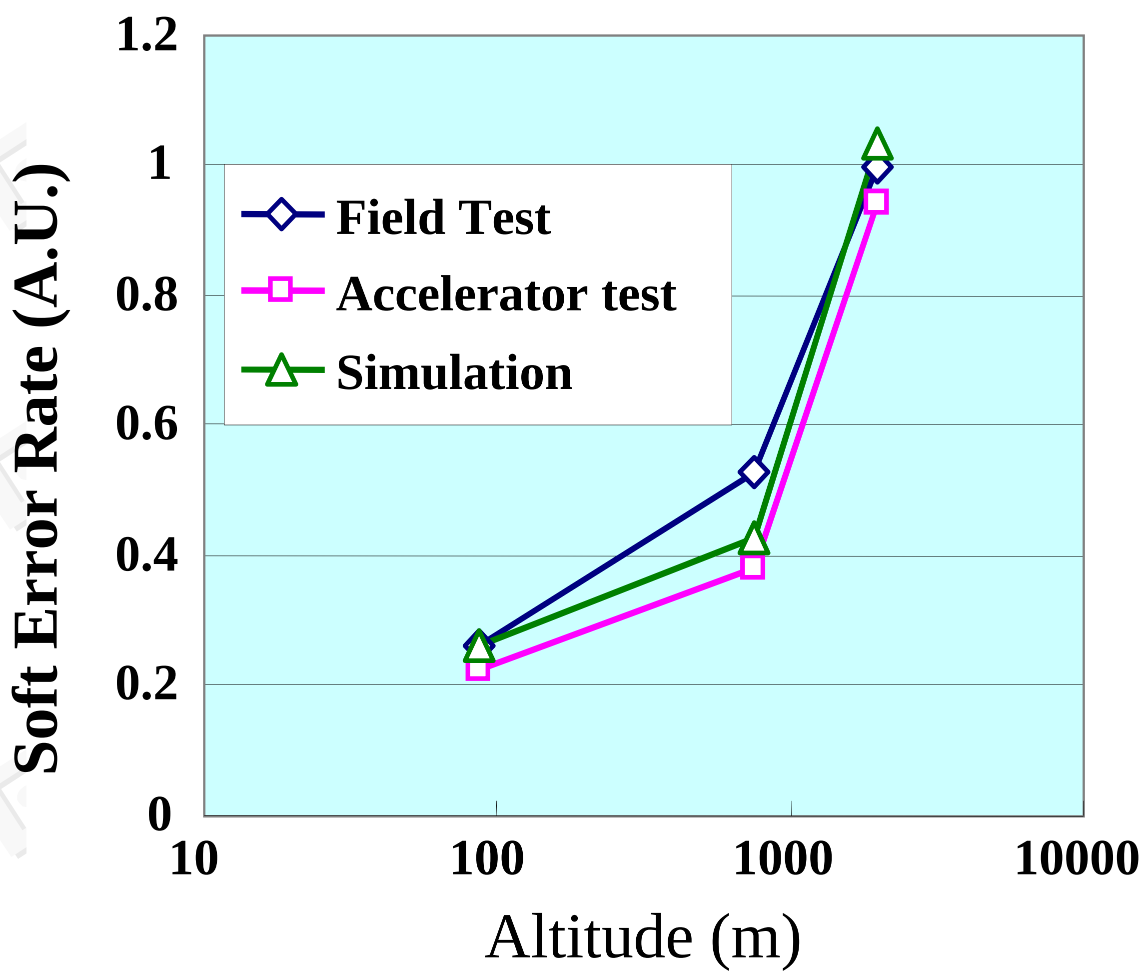
Example of Approximation Function for LET (Major ions in Si_3N_4 substrate)

78 elements x8 substrates x2 (electric loss + nuclear loss) =
1248 sets of approximation function (from SRIM)

$$Log_{10}\left(\left. \frac{dE_p}{dx} \right|_{sub} \right) = a_{sub}^{p}(E_p)s^2 + b_{sub}^{p}(E_p)s + c_{sub}^{p}(E_p) \quad (s=\mathrm{Log}_{10}(E_p))$$

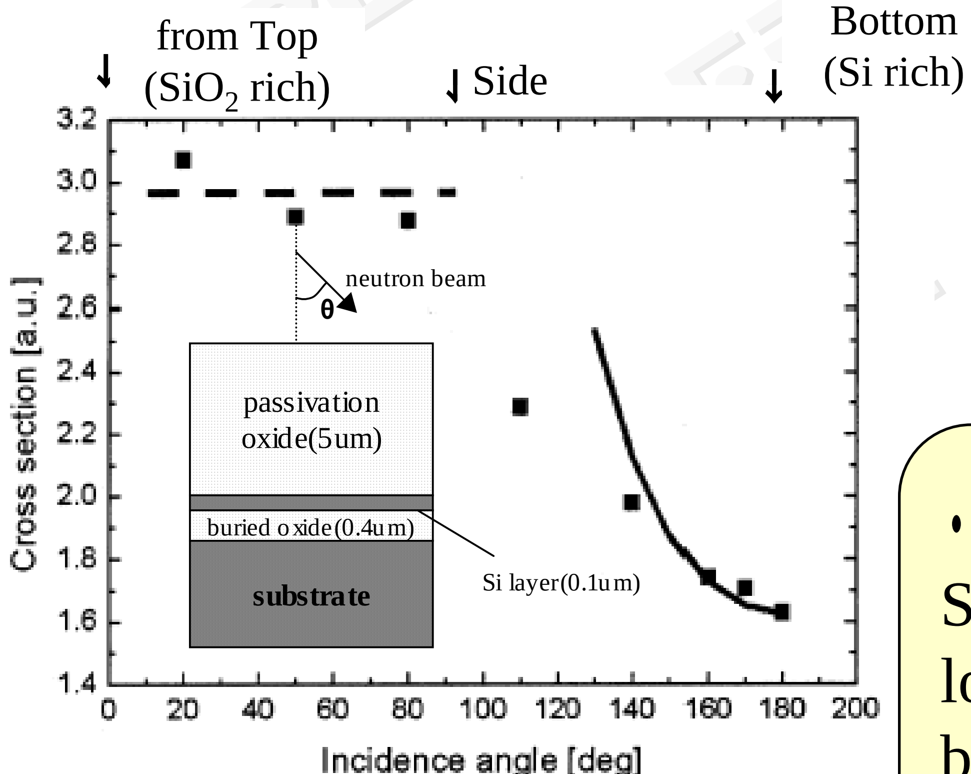


Soft-error Rates from Field test/ Estimated (Accelerator Test) Simulation for 0.18μm process SRAM (CORIMS)



Possible Material Effects(Si/SiO_2) on Neutron Soft Error

G. Gasiot,, IEEE Transactions on Nuclear Science, Vol. 49, No. 6, pp.3032-3037(2002)

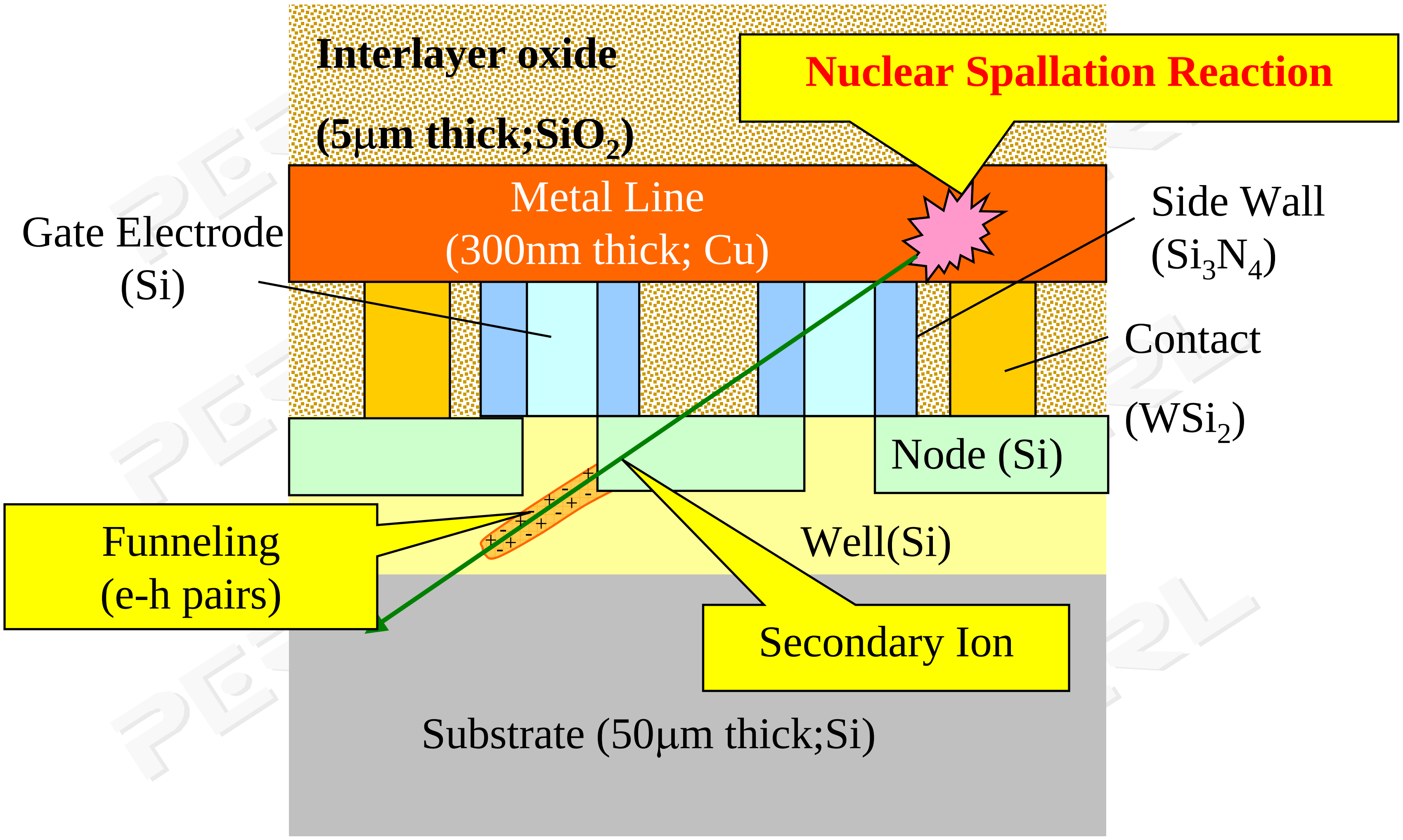


- Error rate (cross section) depends on the direction of 14 MeV neutron beam

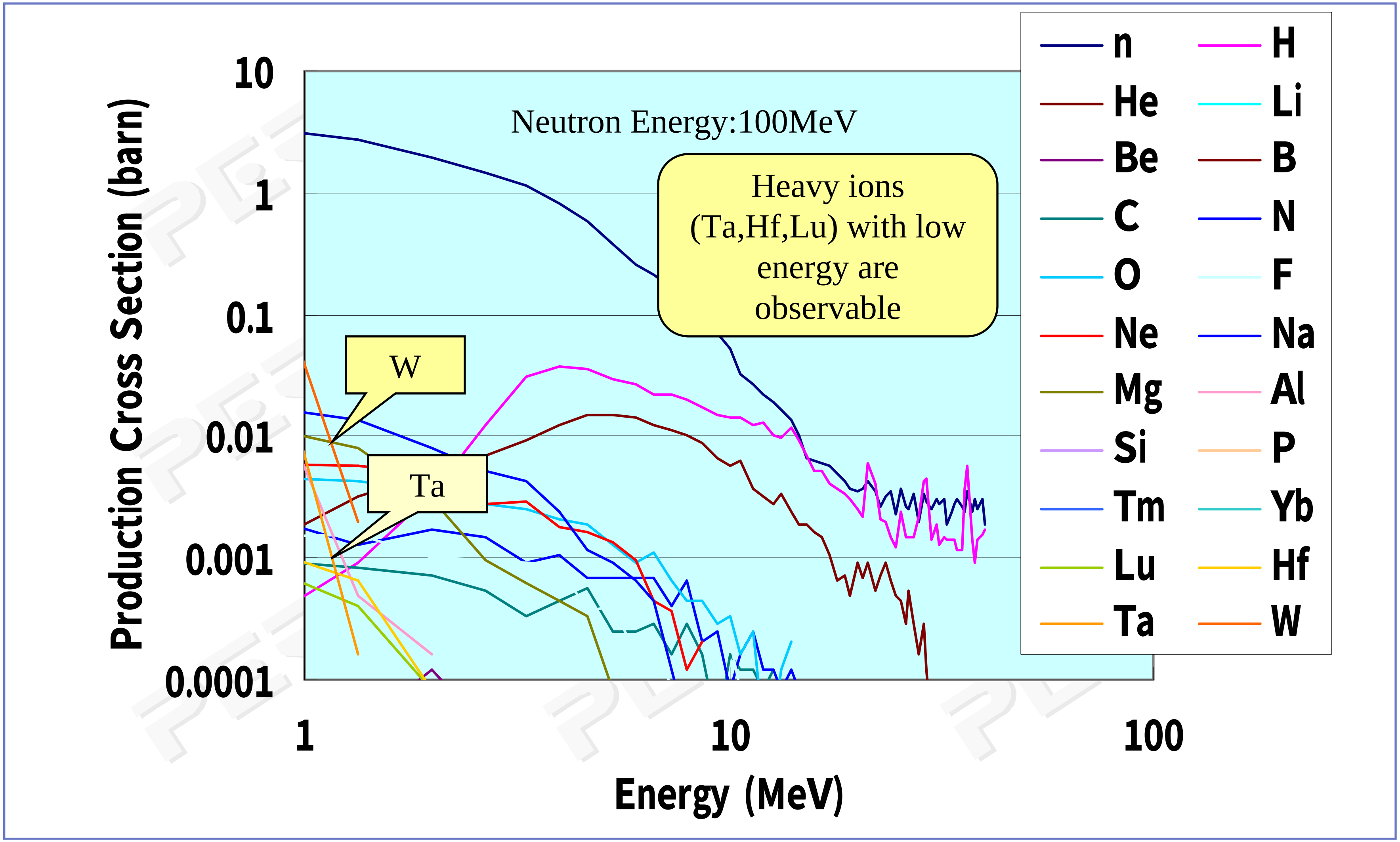
Assumption

- Secondary ions from SiO_2 (N,C) with ranges longer than Al,Mg may be dominant.

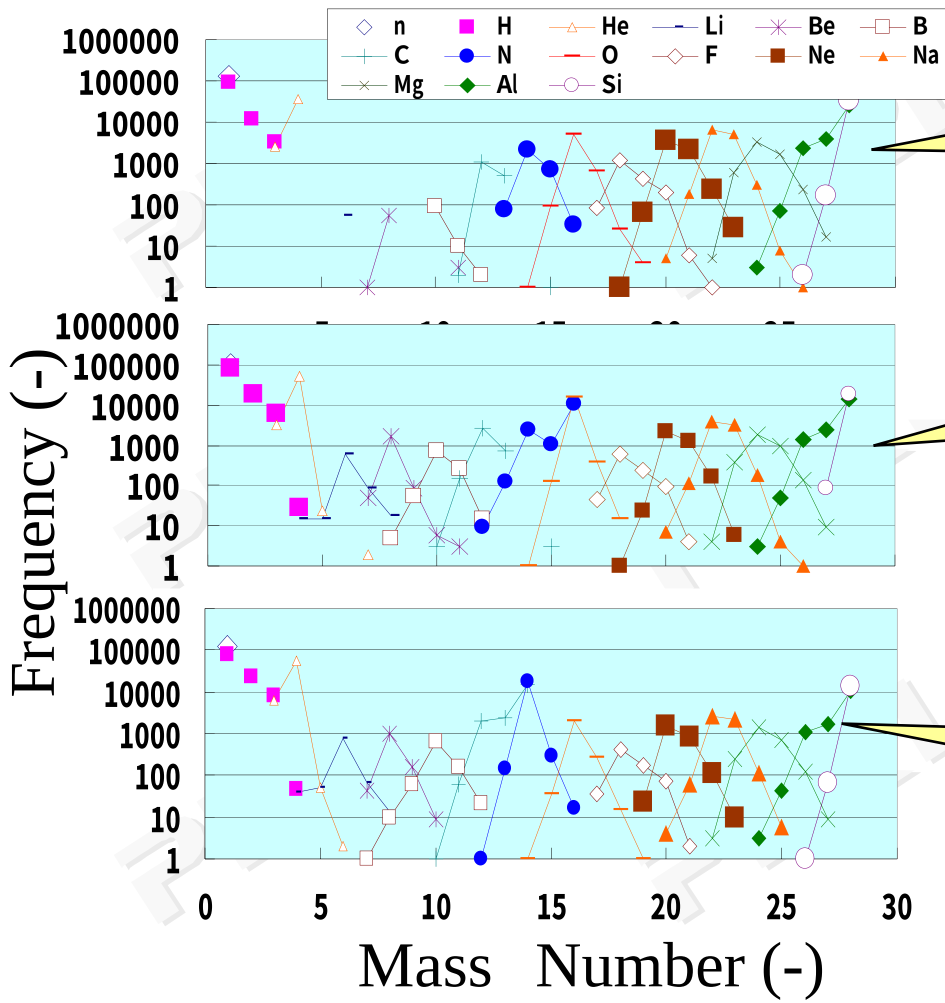
Virtual Device Model (SEALER)



Energy Spectra of Secondary Ions from WSi_2 Substrate



Difference in Produced Secondary Ions upon Substrates



Neutron energy : 100MeV

Si substrate

Major secondary ions:

Si, Al, p, α

SiO_2 substrate

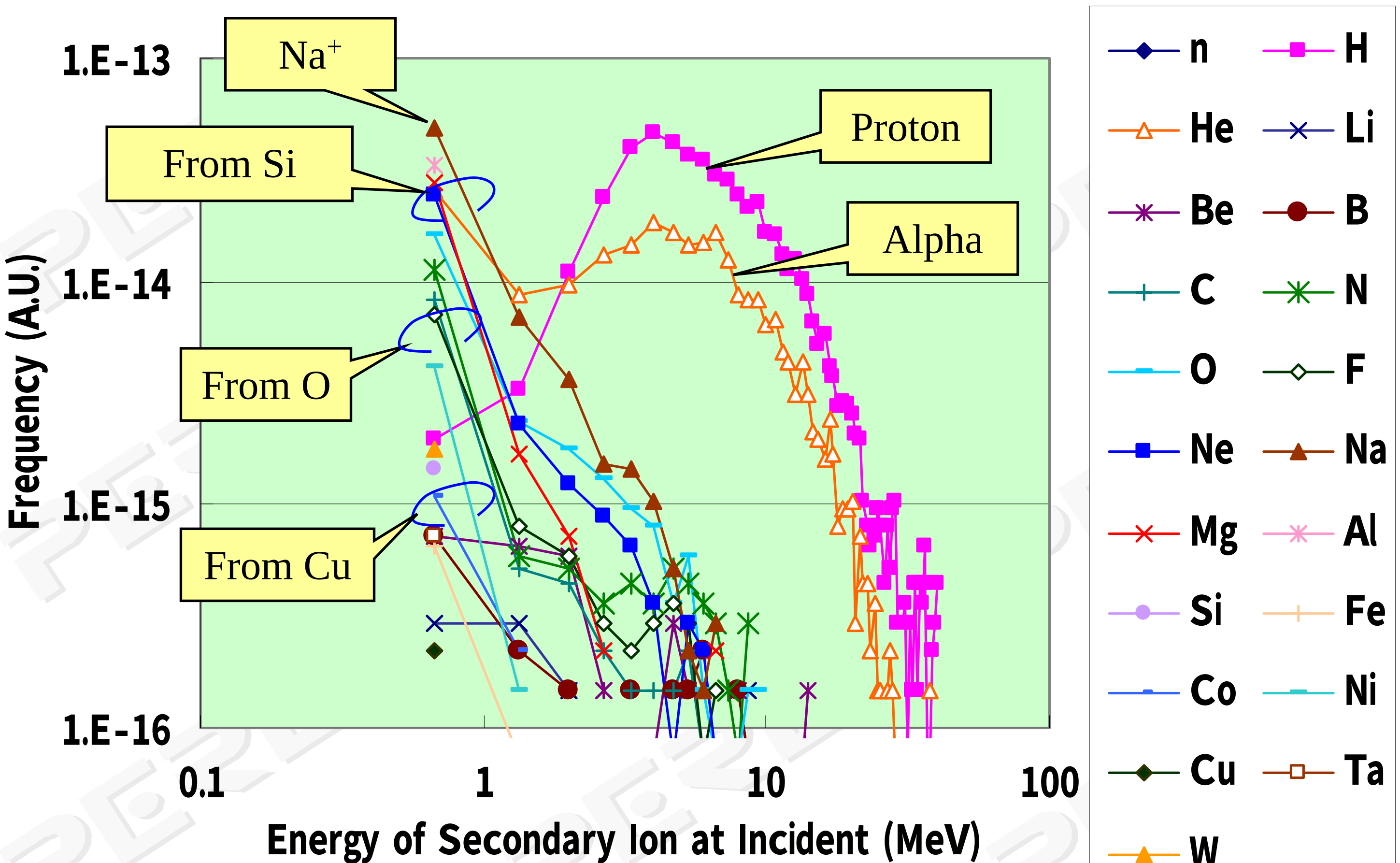
Si, Al, p, α, O, N

Si_3N_4 substrate

Si, Al, p, α, C, N

Ions with longer range than Si, Al

Example of Simulation Results for Virtual Device: Secondary Ions which Pass-through Error Sensitive Node



No direct relationship with the amount produced: Heavier ions do not have ranges long enough to reach nodes

Summary

- MONTE-CARLO simulator SEALER was developed to deal with neutron induced soft-error in all possible materials in semiconductor devices.
- The effects of secondary ions like C,N from SiO_2, Si_3N_4 on soft-error may be underestimated by Si-only model.
- The amount of secondary ions passing through sensitive node depend on positions of various components with different materials; does not necessary correspond to the amount of secondary ions produced.
- Heavier secondary ions (from Cu, W, Ta) may have only local (spatially limited) effects.

(Personally and Selfish) Preferable Linkage between Nuclear Science and Silicon Technology

■ **Generalized library** of simple functional expression of nuclear data in .dll files, for example, which can be handled easily by VB or C development platform like:

Incident particle (p/n)
Target Nucleus
Reaction type

Function GetSigma (Energy, Angle, Incidence, Target, Type, ….)

Maximum acceptable run time: few milliseconds per shot

■ **Co-operative standardization of accelerator neutron tests in SEE**.

- First stage completed in USA as "JESD89" issued in 2002
- World-wide task group to renew JESD89 started in 2004 (70 members) (US chair:TI; Europe chair:Infinion; Asian /Pacific chair: Hitachi)