ミニワークショップ「核データと核理論」
＠理化学研究所　 2009.3.25-26

高エネルギー核データの現状とその応用

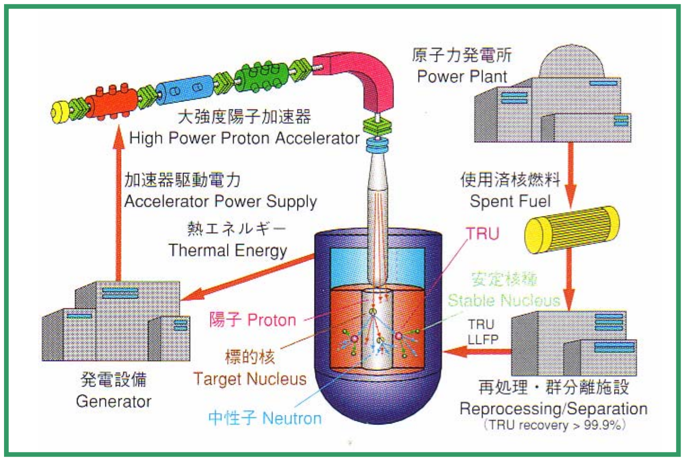
九大･総理工　渡辺幸信

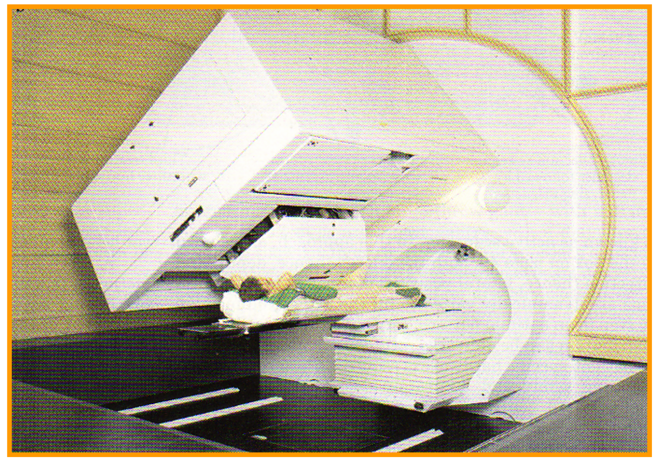
内　容

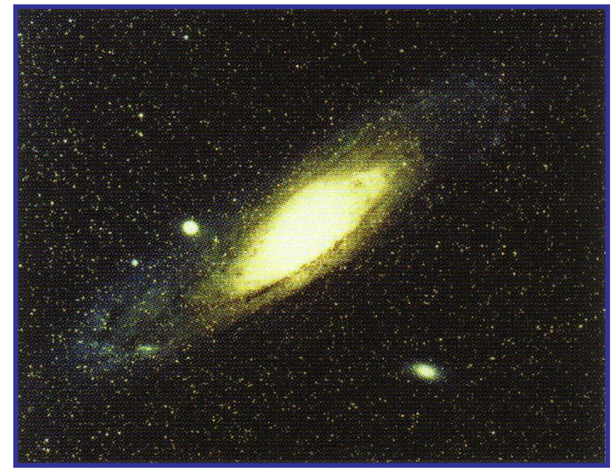
- 高エネルギー核データニーズ
- 国内における高エネルギー核データ評価活動
  - JENDL High-energy ファイル
- 応用例と必要な核データ
  - 半導体ソフトエラー研究
  - 核融合研究関連
- まとめ

Needs of high-energy nuclear data

Various applications fields relevant to "high-energy nuclear data"







Accelerator applications

- Accelerator design (Shielding calculation, Activity estimation)
- Nuclear waste transmutation (Particle transport calculation)

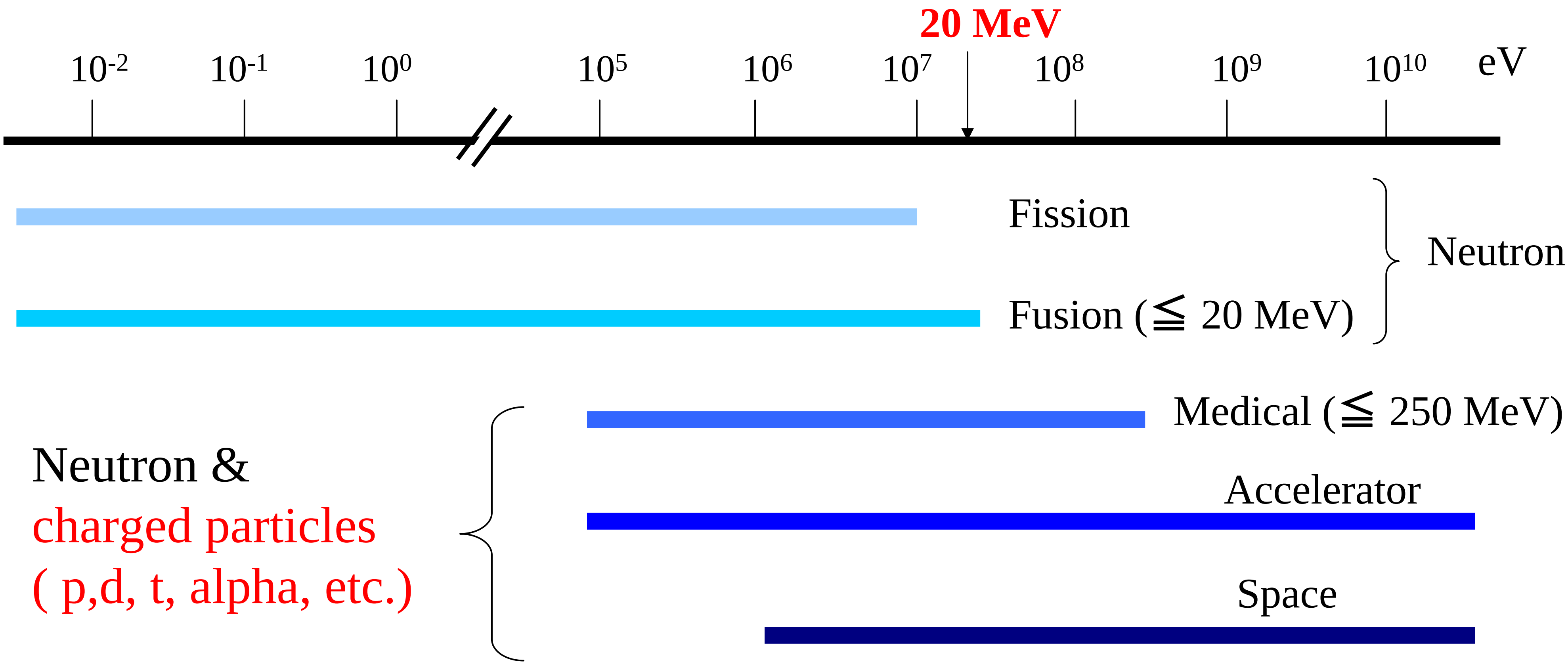
Medical applications

- Advanced radiation therapy
- Medical radioisotope production

Astrophysics, Space Engineering

- Study of origin of material and comic-rays
- Estimation of radiation dose for space ships and astronauts
- Radiation damage on microelectronics by cosmic-rays

Energy region required for high-energy nuclear data



- Extension of incident energy range beyond 20 MeV
- Inclusion of protons and other light-ions (d, t, alpha,etc.) as incident particles

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JENDL high-energy file project

- JENDL = Japanese Evaluated Nuclear Data Library

  汎用ファイルの最新版:　JENDL-3.3 (2002)
  → 20MeV以下中性子, 337 核種
  (JENDL-4:来年度末公開予定)

- シグマ委員会　高エネルギー核データ評価WG:　16 名(H20年度)
  産官学連携プロジェクト
  （JAEA, 東工大, 九大, KEK, RIST, 日立、清水建設等）

JENDL High-Energy file (JENDL-HE)

Continued

Contents of JENDL High-Energy file (JENDL-HE)

- Nuclides : Total 132
  1^{st} Priority (39 nuclides), 2^{nd} (43), 3^{rd} (40), 4^{th} (10)

- Upper limit of incident energy : 3 GeV for neutron and proton

- Type of cross sections

  - Total, Elastic, Non-elastic cross sections
  - Light particles and gamma-ray production cross sections and DDXs（n, p, d, t, ^{3}He, α, pions, and γ）
  - Isotope production cross sections
  - Fission cross sections

- Data format: ENDF-6

List of Nuclei

1st priority (39)	^{1}H, ^{12}C, ^{14}N, ^{16}O, ^{27}Al, ^{50,52,53,54}Cr, ^{54,56,57,58}Fe, ^{58,60,61,62,64}Ni, ^{63,65}Cu, ^{180,182,183,184,186}W, ^{196,198,199,200,201,202,204}Hg, ^{204,206,207,208}Pb, ^{209}Bi, ^{235,238}U
2nd priority (43)	^{9}Be, ^{10,11}B, ^{24,25,26}Mg, ^{28,29,30}Si, ^{39,41}K, ^{40,42,43,44,46,48}Ca, ^{46,47,48,49,50}Ti, ^{51}V, ^{55}Mn, ^{59}Co, ^{90,91,92,94,96}Zr, ^{93}Nb, ^{92,94,95,96,97,98,100}Mo, ^{238,239,240,241,242}Pu
3rd priority (40)	^{2}H, ^{6,7}Li, ^{13}C, ^{19}F, ^{23}Na, ^{35,37}Cl, ^{35,38,40}Ar, ^{64,66,67,68,70}Zn, ^{69,71}Ga, ^{70,72,73,74,76}Ge, ^{75}As, ^{89}Y, ^{181}Ta, ^{197}Au, ^{232}Th, ^{233,234,236}U, ^{237}Np, $^{241,242,242m,\ 243}$Am, ^{243,244,245,246}Cm
4th priority (10)	^{15}N, ^{18}O, ^{74,76,77,78,80,82}Se, ^{113,115}In

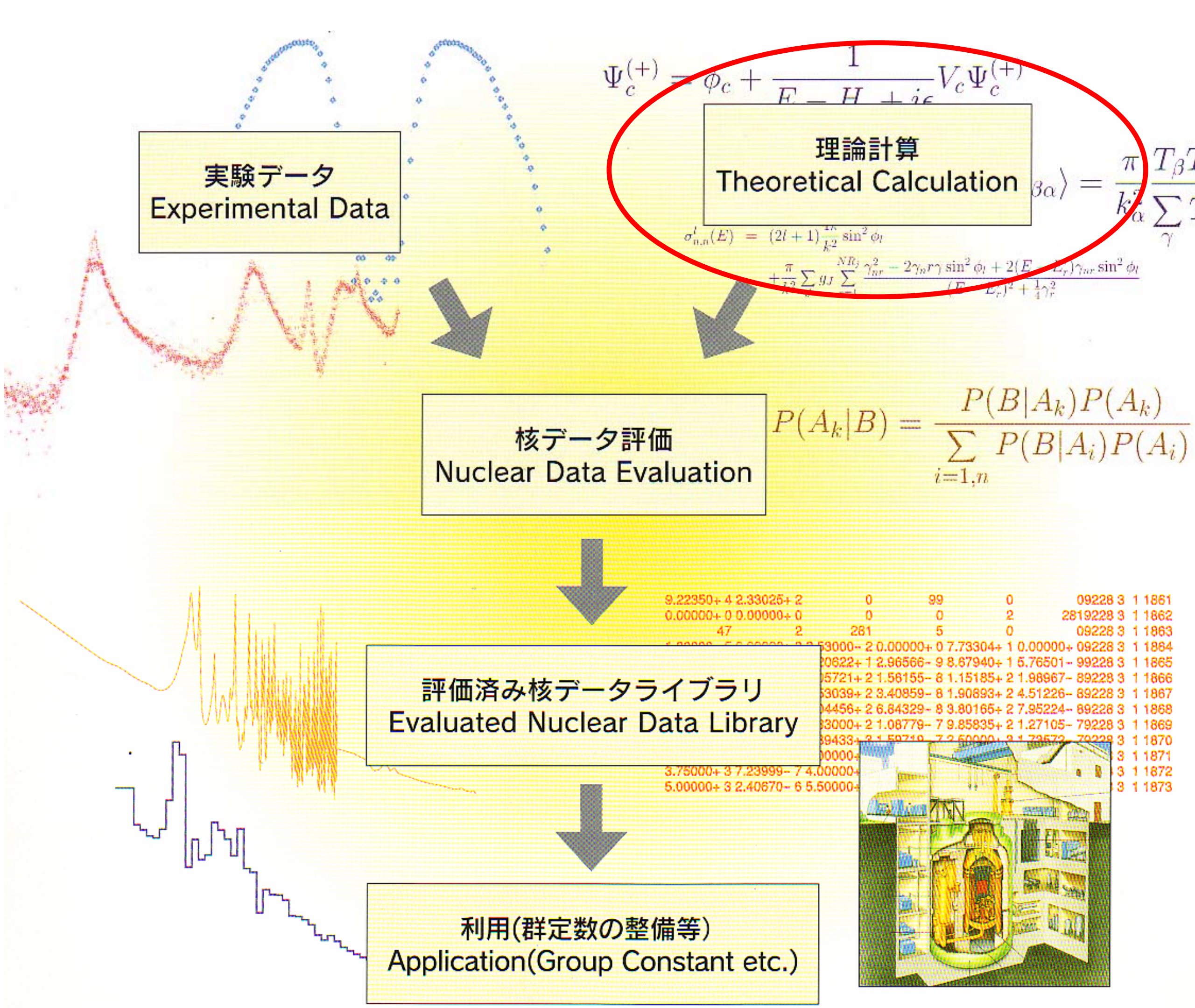
Released as JENDL/HE-2004 (66 nuclei)

Released as JENDL/HE-2007 (66+40=106 nuclei)

It will be released as a supplement in next year

Evaluation is not accomplished yet …

How Do We Produce Nuclear Data for Applications ?



"Nuclear data evaluation" provides the most probable data set by using
- Experimental data,
- Theoretical model calculations,
- Statistics, etc.

Evaluated nuclear data are compiled to numerical data sets having specific formats, e.g., ENDF-6

These data sets are processed according to user's requirements

Overview of high-energy nuclear reactions

10^{-22} sec

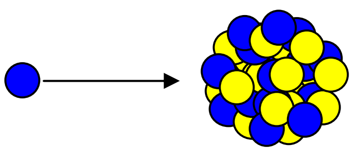
$10^{-15} \sim 10^{-19}$ sec

Elastic Scattering

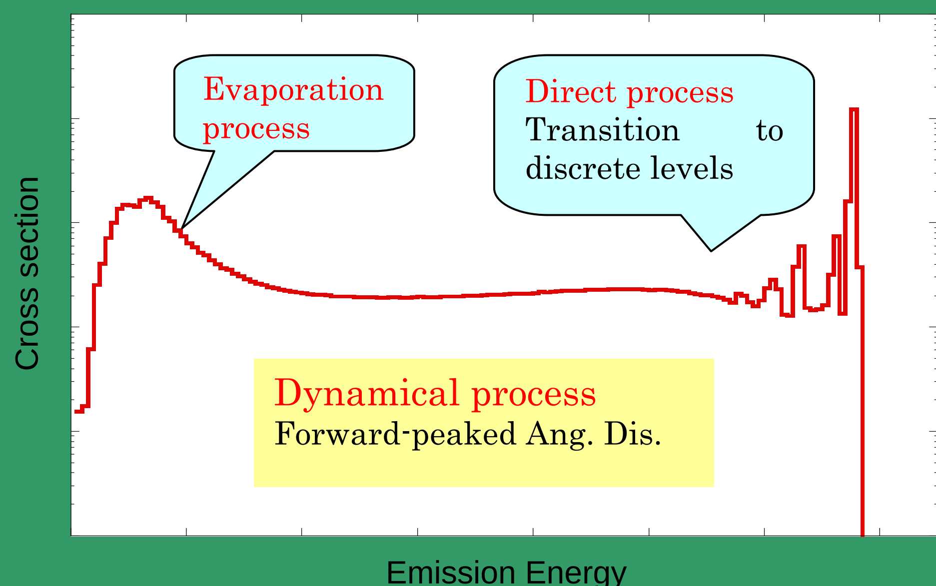
Direct Process
Collective excitation
Quasi-Elastic Scat.

Highly excited Nuclei
Evaporation

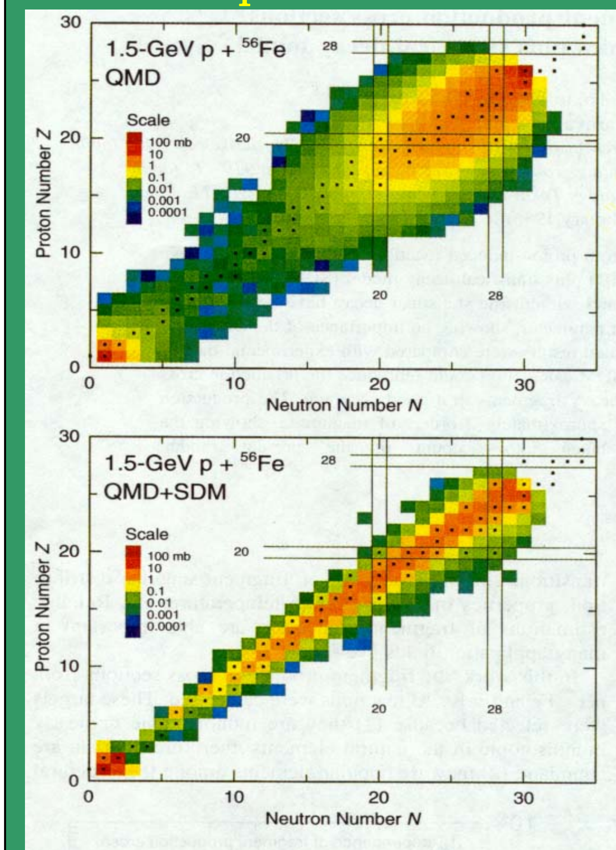
Dynamical Processes
- Preequilibrium Process
- Intra-Nuclear Cascade Process
- Multi-fragmentation Process



Energy Spectrum of Emitted Particles



Isotope Production

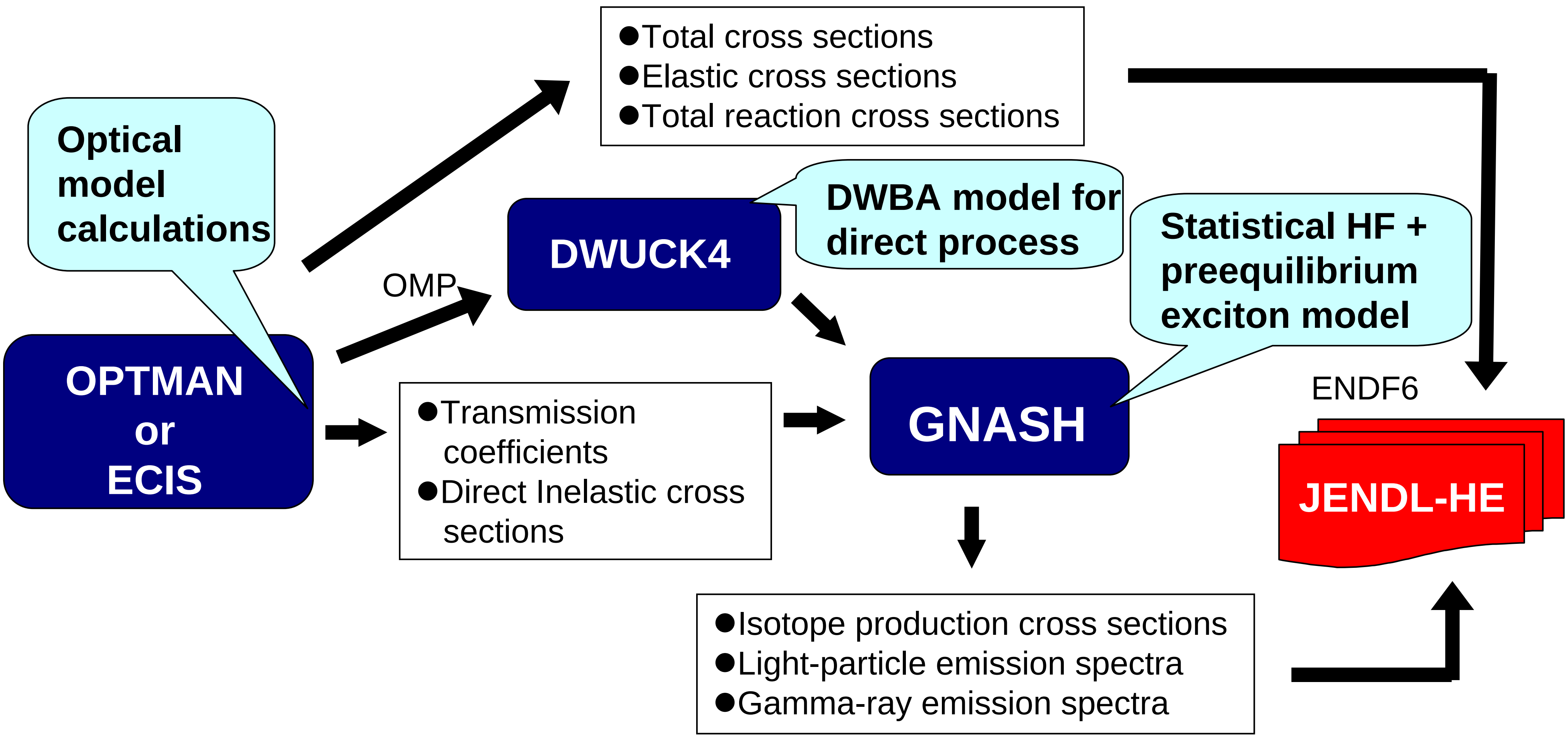


Ref.) Chiba et al., Phys. Rev. C 54 (1996) 285.

Hybrid nuclear model code system (I)

Intermediate energies

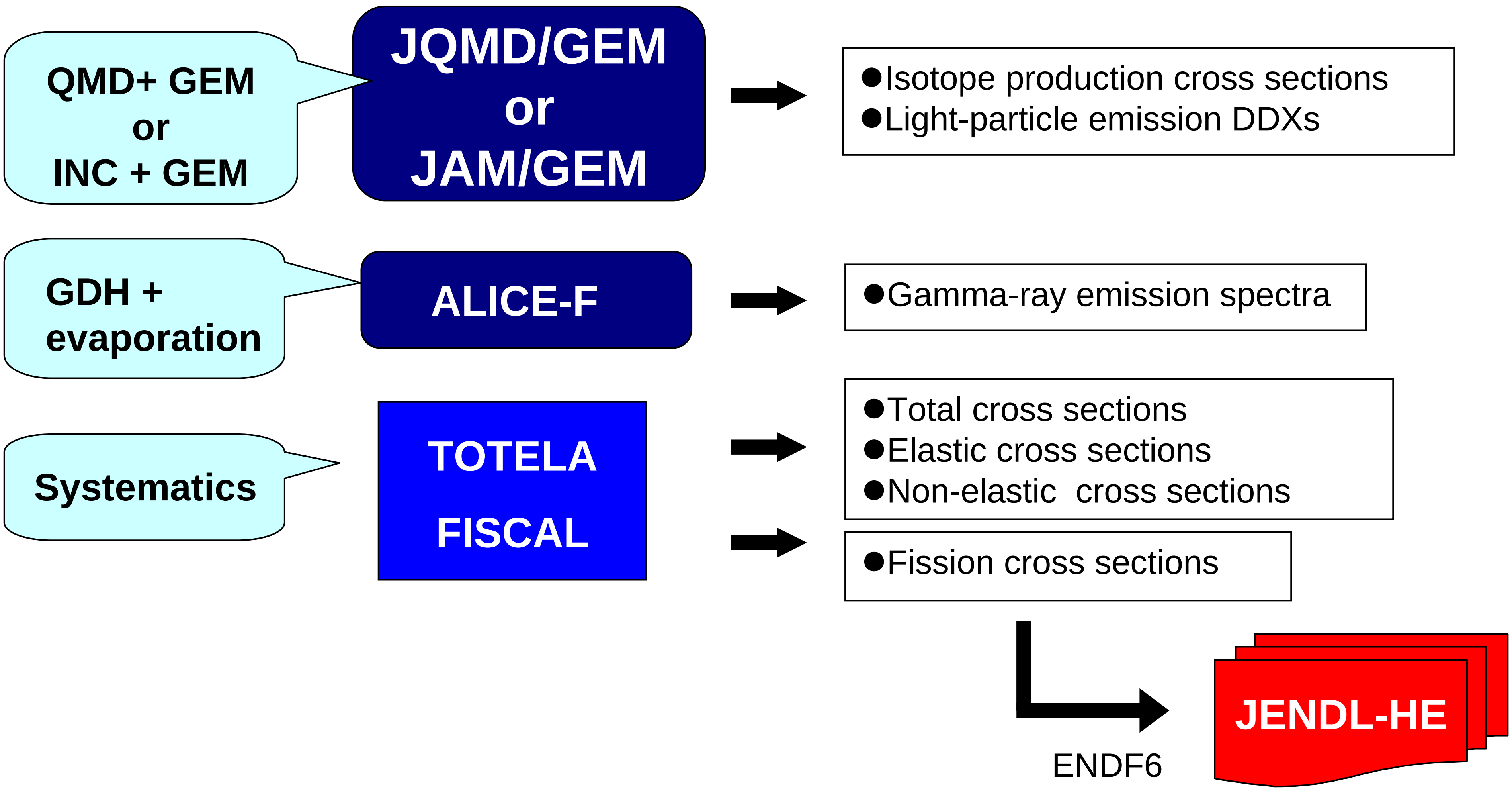
$E_{inc} \leq 150 - 250$ MeV



Hybrid nuclear model code system (II)

Higher energies

$E_{inc} \geq 150 - 250$ MeV



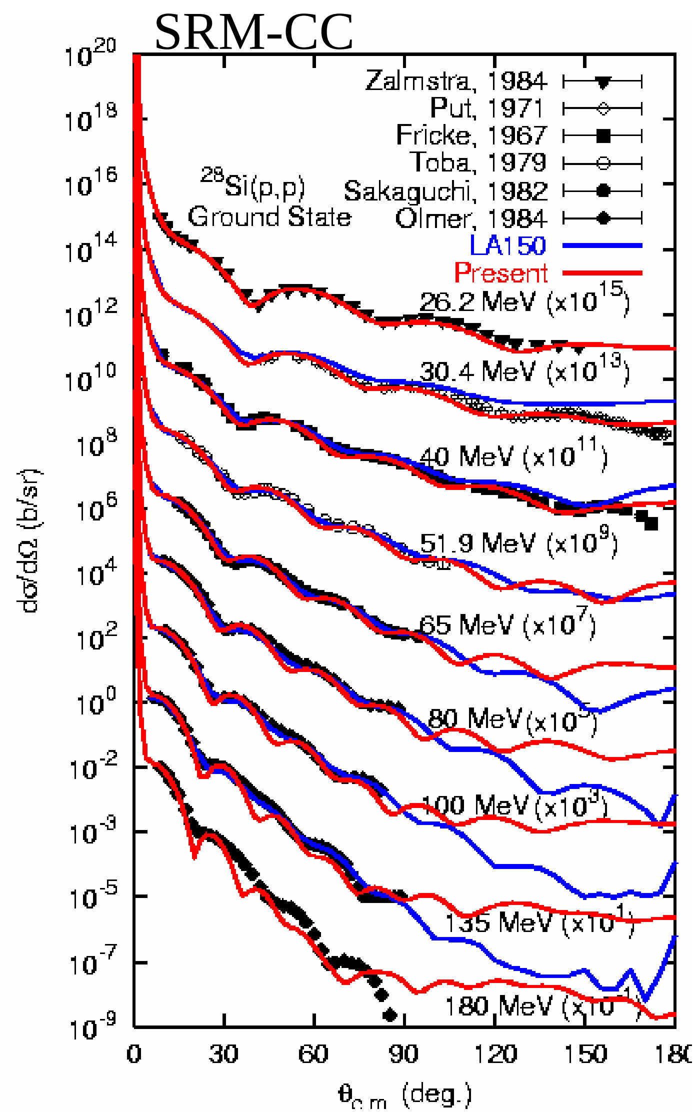
Optical Model Analysis (<200 MeV)

Model :

- Coupled-channel OM (RRM/SRM)
  - ⟶ Deformed Nuclei
- Spherical OM + DWBA
  - ⟶ (Near-) spherical Nuclei

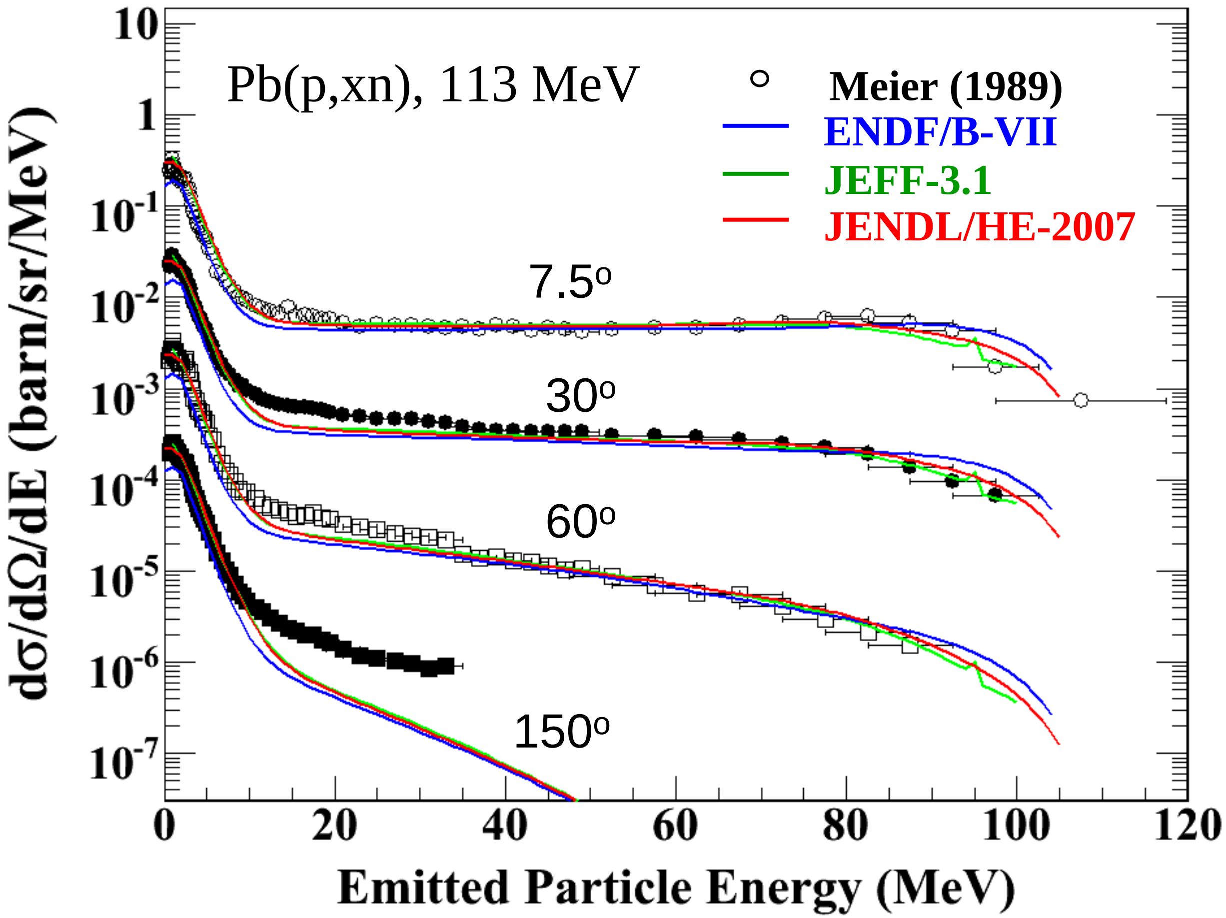
Optical Potential (OMP) :

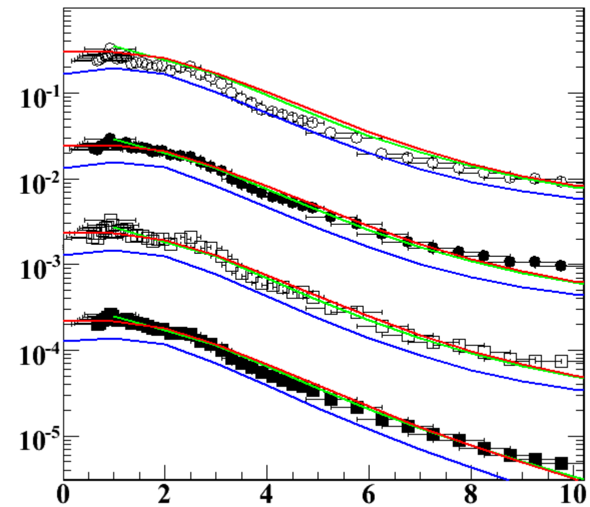
- Continuous local/global (<200MeV)
- Isospin-dependent
  (Soukhovitskii's framework)
- Global / folding OMP for d, t, h, α



GNASH Calculation

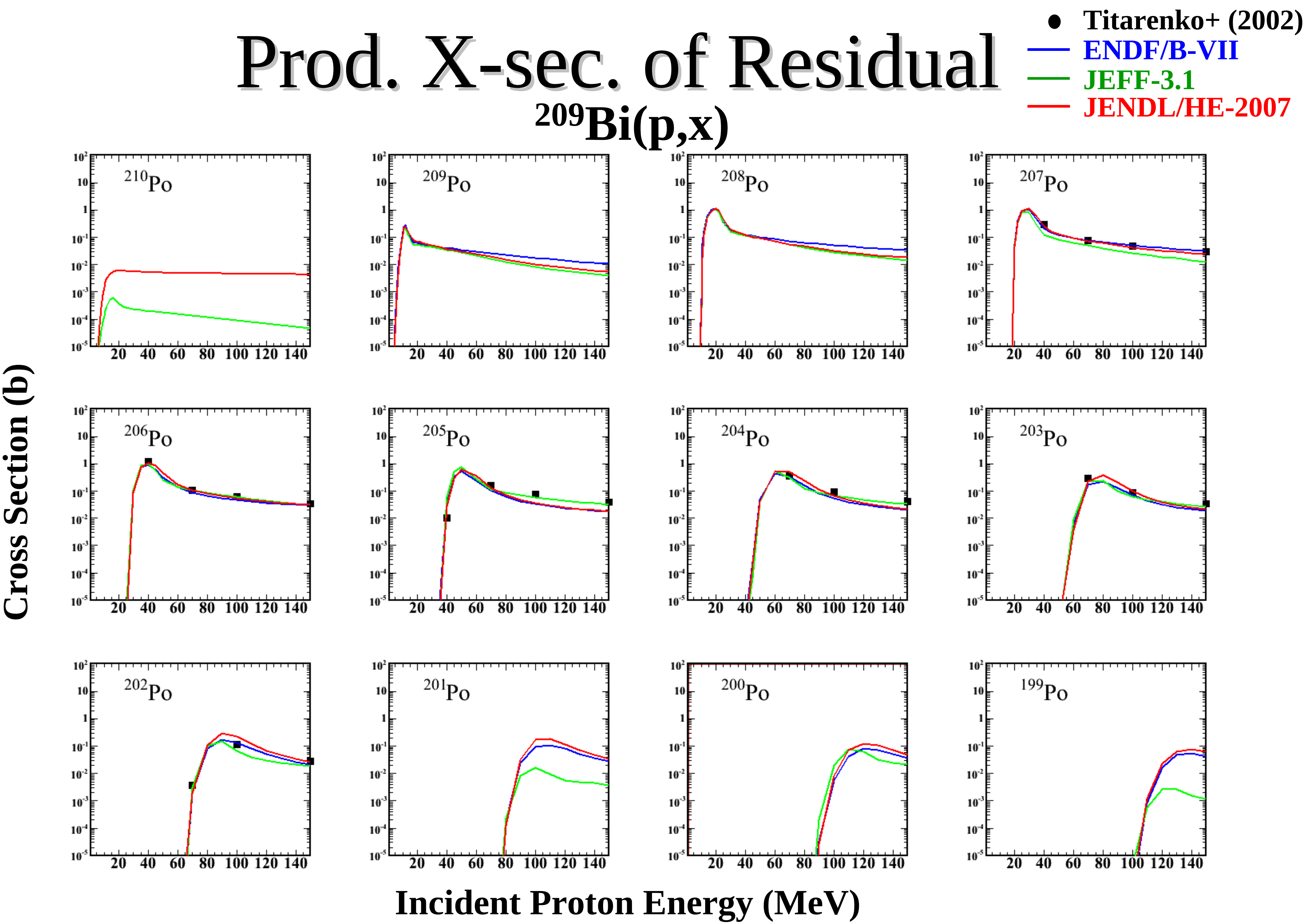
OM + Statistical + Pre-equilibrium model + Kalbach's syst.





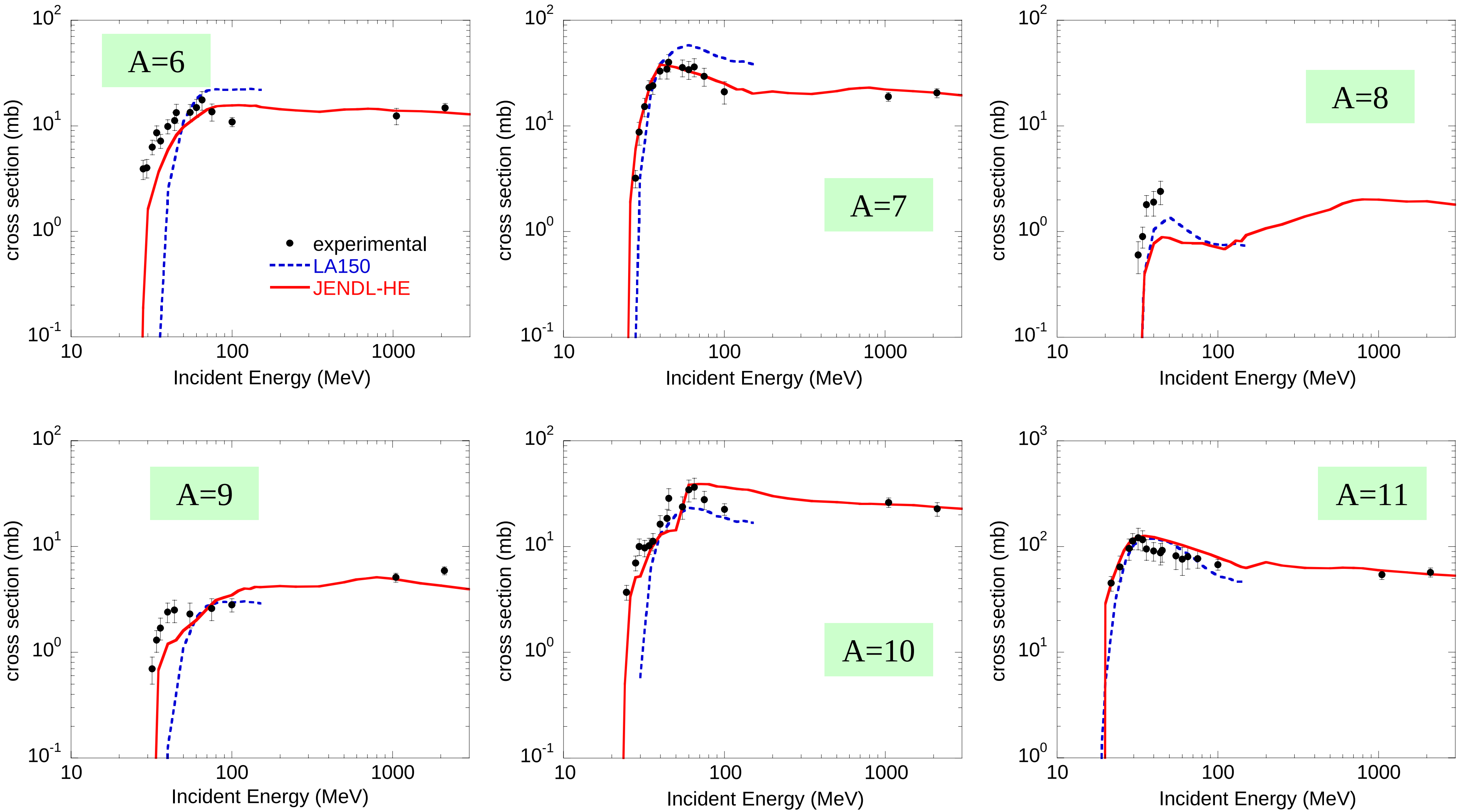
Prod. X-sec. of Residual

$^{209}Bi(p,x)$



Isobar production cross section for p+ ^{12}C

Nuclear data related to nucleosynthesis of light elements induced by cosmic-rays



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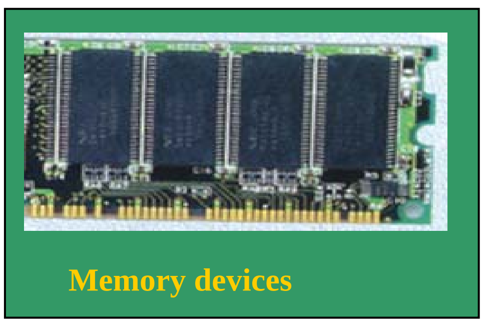
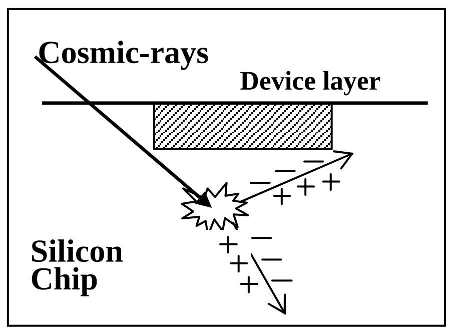
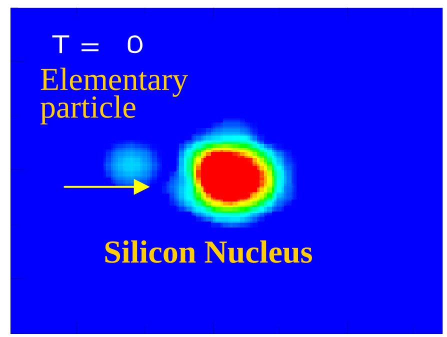
Cosmic-rays induced single-event upsets in microelectronics and related nuclear reaction database

- The role of nuclear physics in IT society -





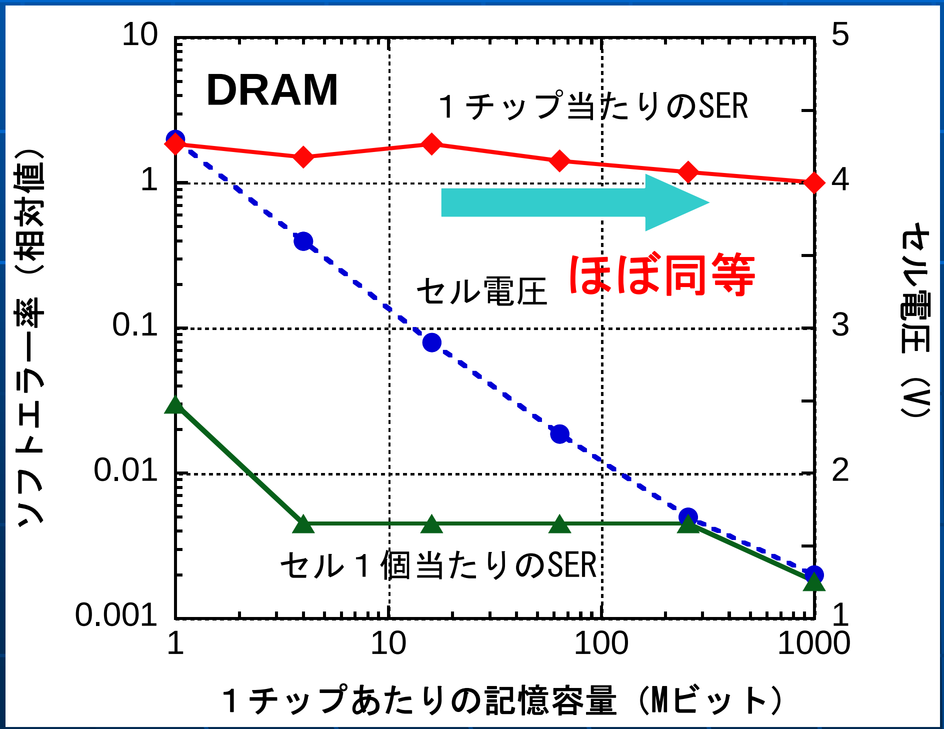


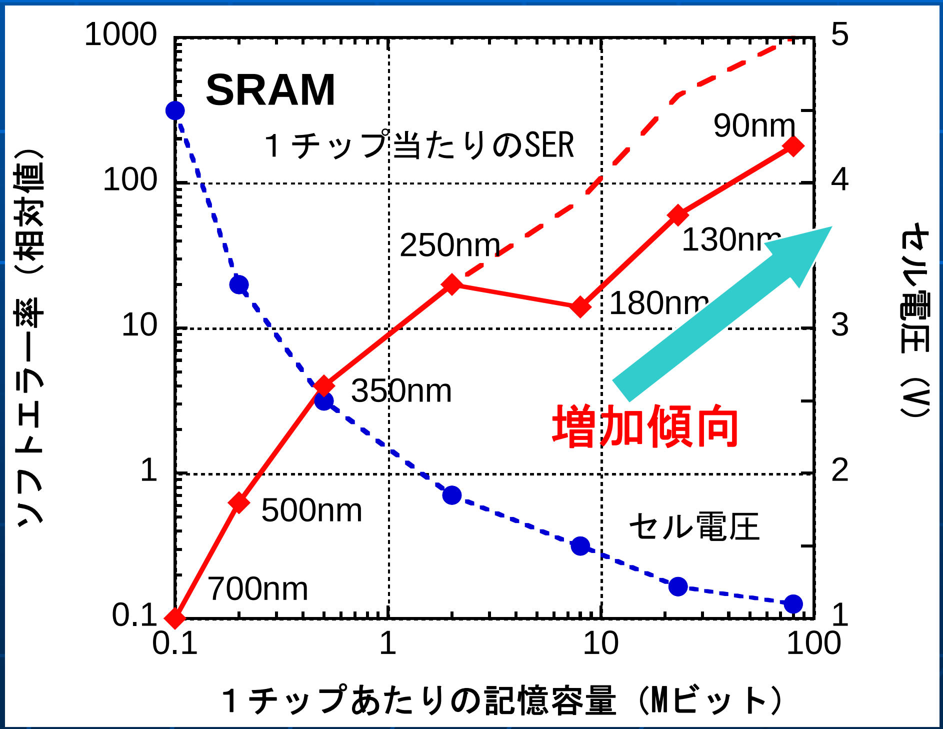
研 究 背 景

LSIの微細化・高密度化 ⇨ ソフトエラー率の増大が懸念

DRAM, SRAM ⇒ 論理回路

ソフトエラー： ある種の放射線がLSIと衝突することによって、LSIが一過性の誤動作を起こす現象





引用） 日経エレクトロニクス2005.7.4

ソフトエラー・メカニズム： 放射線源

放射線

⇩

電子-正孔対生成

⇩

ノイズ誘起

放射線源

1) α線（放射性同位元素不純物：U, Th, Po）

2) 熱中性子(< 1eV): BPSG膜中の^{10}Bとの相互作用で生成したα粒子と^{7}Liイオン

3) 高エネルギー宇宙線中性子(MeV～GeV)による核反応で生成した各種二次イオン

Forbes.com

November 13, 2000

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

Sun Screen

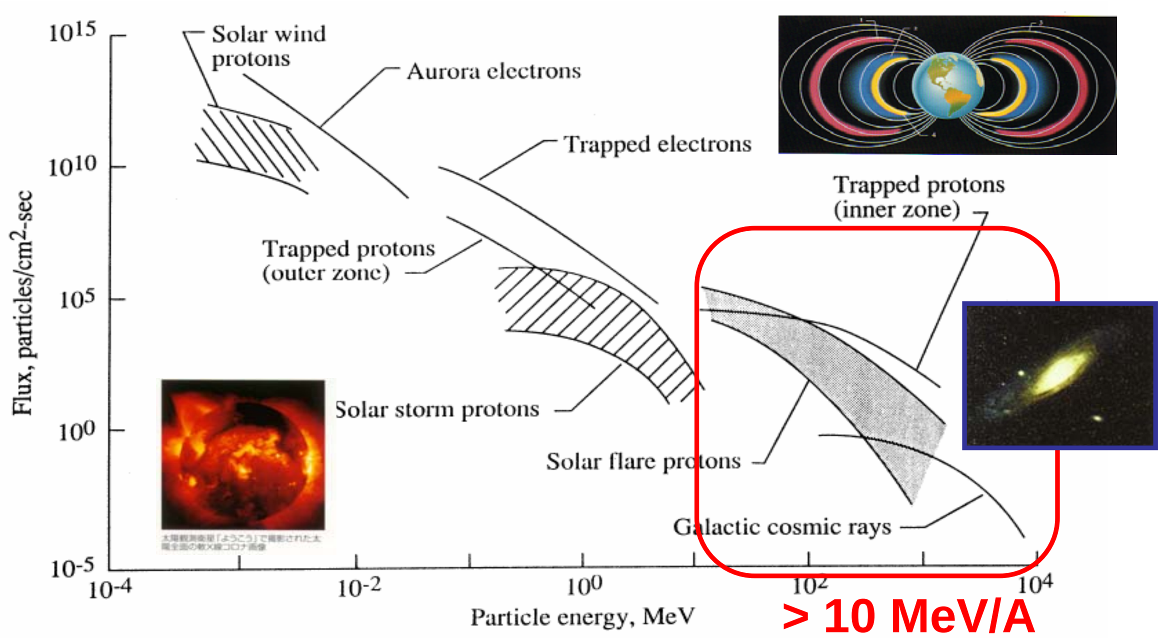
THE MYSTERIOUS GLITCH has been popping up since late last year. At a new Web company in San Francisco, a telecommunications company in the Midwest, a Baby Bell in Atlanta, an Internet domain registry on the East Coast--for no apparent reason, **high-end servers made by Sun Microsystems suddenly crashed**.

. . . . . .

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

Cosmic-ray environment

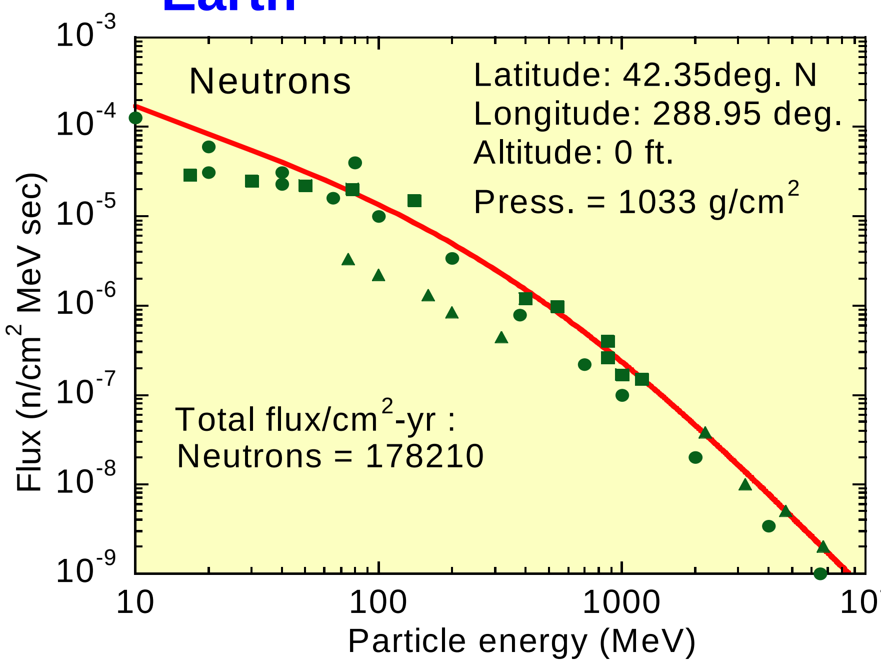


Cosmic-rays in Space

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

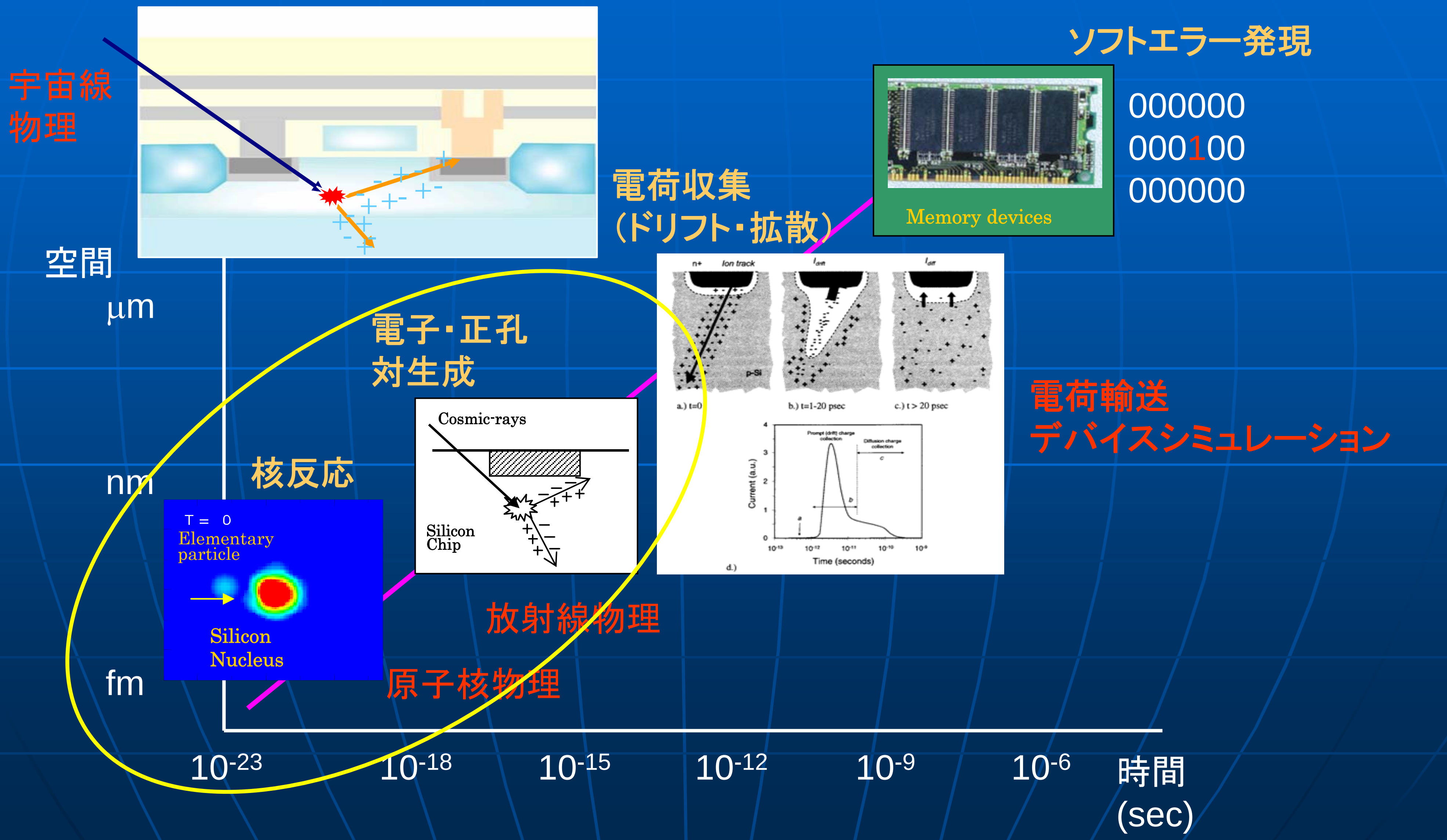
Neutron flux @Tokyo
about 12 n/cm² h
for above 10 MeV

Secondary cosmic-ray neutrons at sea level on the Earth



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

宇宙線中性子起因ソフトエラー発現へ至る物理過程の時間･空間発展



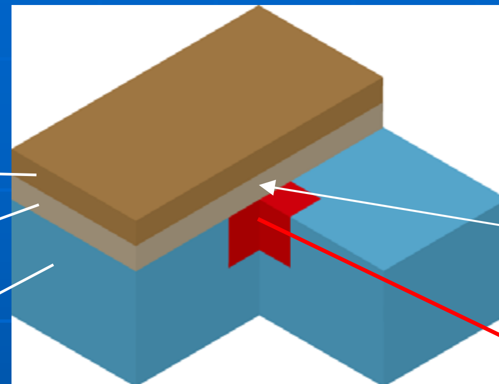
生成2次イオン電荷付与

MOSFETを模擬

配線層（Cu : SiO_2 = 1 : 1）

絶縁層（SiO_2）

反応領域（Si）

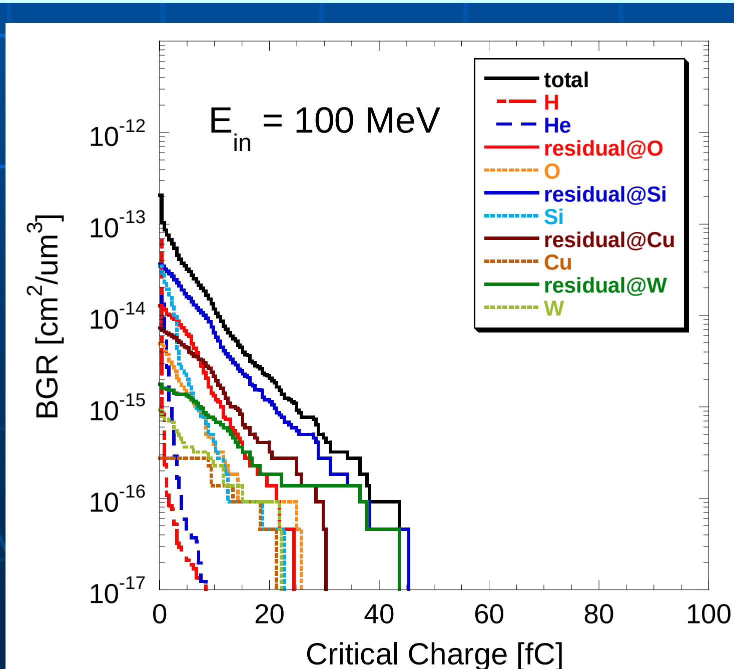


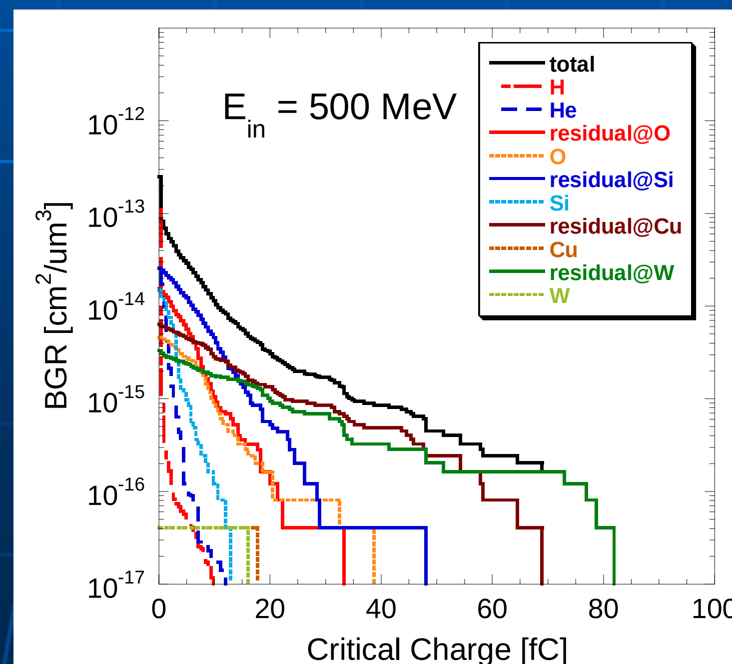
PHITSコード使用
- QMD+GEM

W配線も考慮

有感領域（Si）
0.1×0.1×0.5 μm

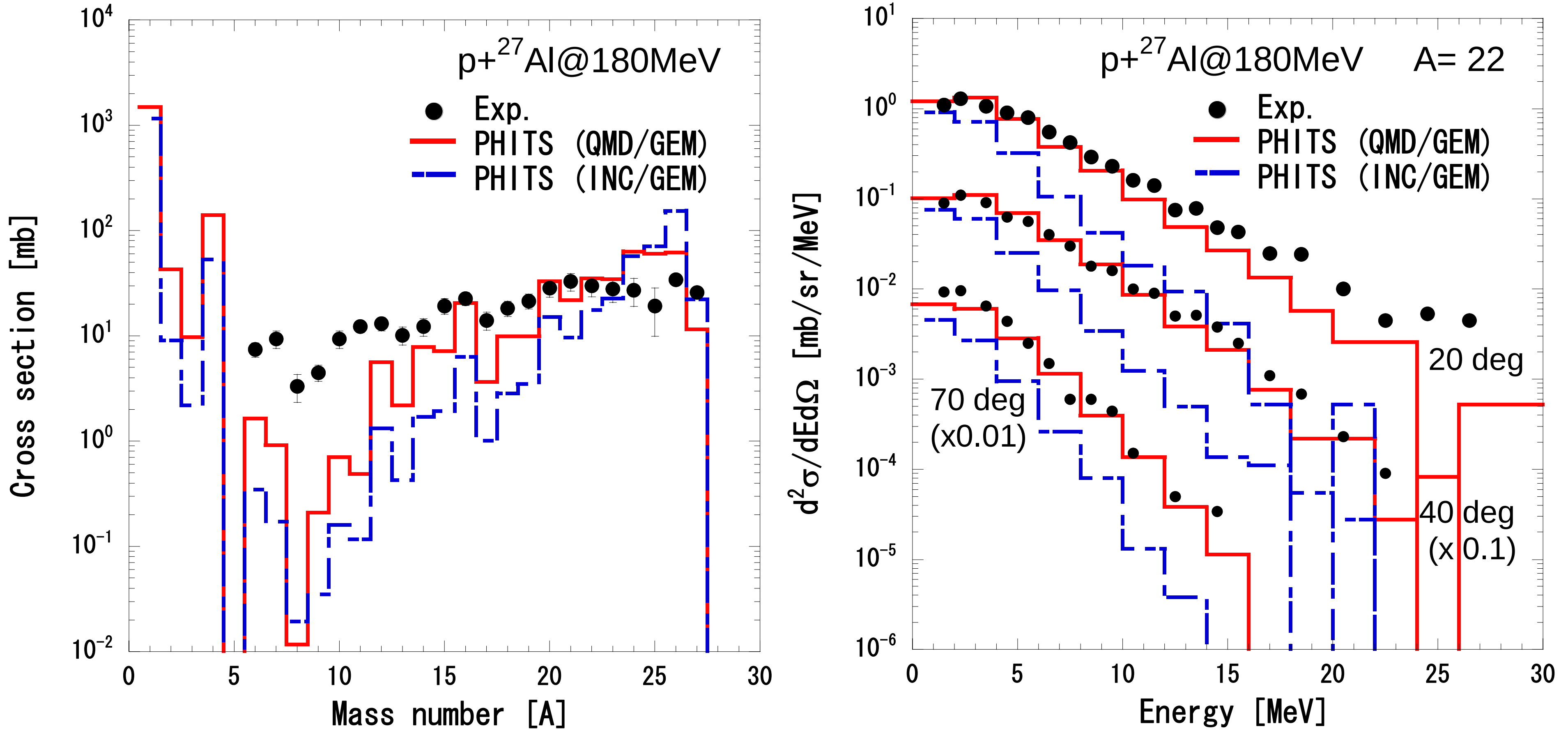
$$BGR(Q_d) = \int_{Q_d}^{\infty} N(q)/(total\ neutron\ \ flux)/(sensitive\ volume)dq$$





モデル計算の比較(QMD vs INC)

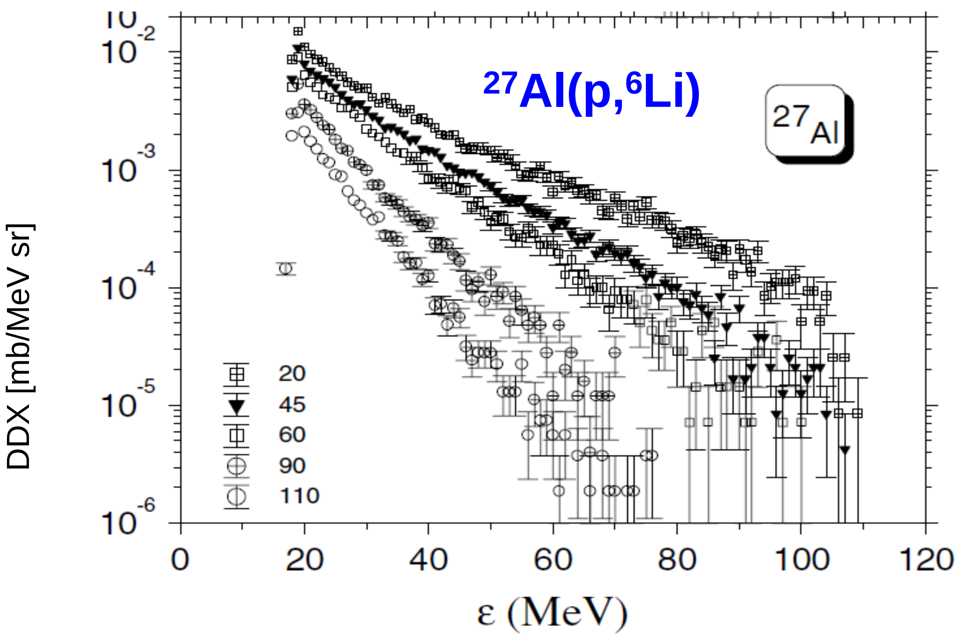
p+^{27}Al@180MeV

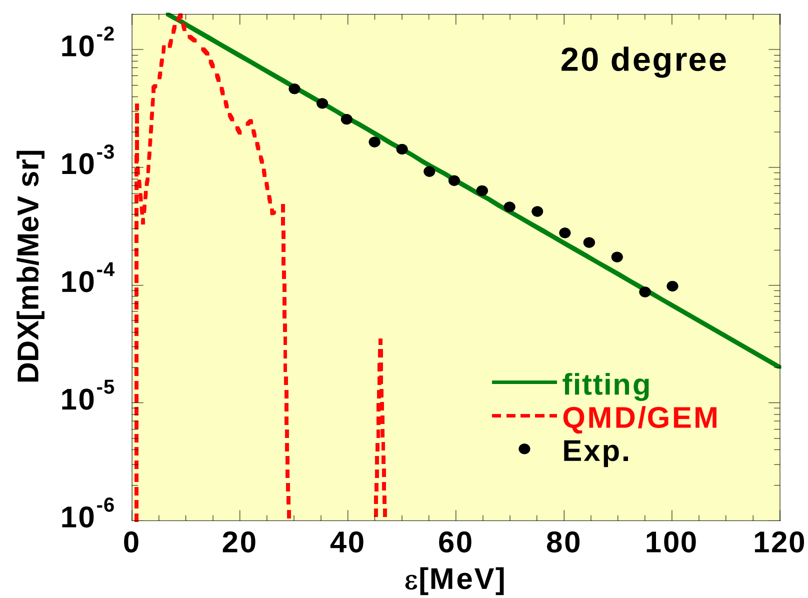


Future requirement for nuclear data

- 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

2次イオン(A>=4)生成実験

PHYSICAL REVIEW C **77**, 044601 (2008)

200 and 300 MeV/nucleon nuclear reactions responsible for single-event effects in microelectronics

H. Jäderström,[1,*] Yu. Murin,[2,3] Yu. Babain,[2] M. Chubarov,[2] V. Pljuschev,[2] M. Zubkov,[2] P. Nomokonov,[3] N. Olsson,[4] J. Blomgren,[5] U. Tippawan,[5] L. Westerberg,[6] P. Golubev,[7] B. Jakobsson,[7] L. Gerén,[8] P.-E. Tegnér,[8] I. Zartova,[8] A. Budzanowski,[9] B. Czech,[9] I. Skwirczynska,[9] V. Kondratiev,[10] H. H. K. Tang,[11] J. Aichelin,[12] Y. Watanabe,[13] and K. K. Gudima[14]

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[3]*Joint Institute for Nuclear Research, JINR, RU-141980, Dubna, Russia*
[4]*Swedish Defence Research Agency (FOI), S-172 90 Stockholm, Sweden*
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[9]*H. Niewodniczanski Institute of Nuclear Physics, 31-342 Cracow, Poland*
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[11]*IBM, T. J. Watson Research Center, Yorktown Heights, New York 10598, USA*
[12]*IN2P3/CNRS, Ecole des Mines de Nantes, 4 rue Alfred Kastler, F-44072 Nantes cedex 03, France*
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(Received 27 November 2007; published 7 April 2008)

反跳核の角度分布

He粒子

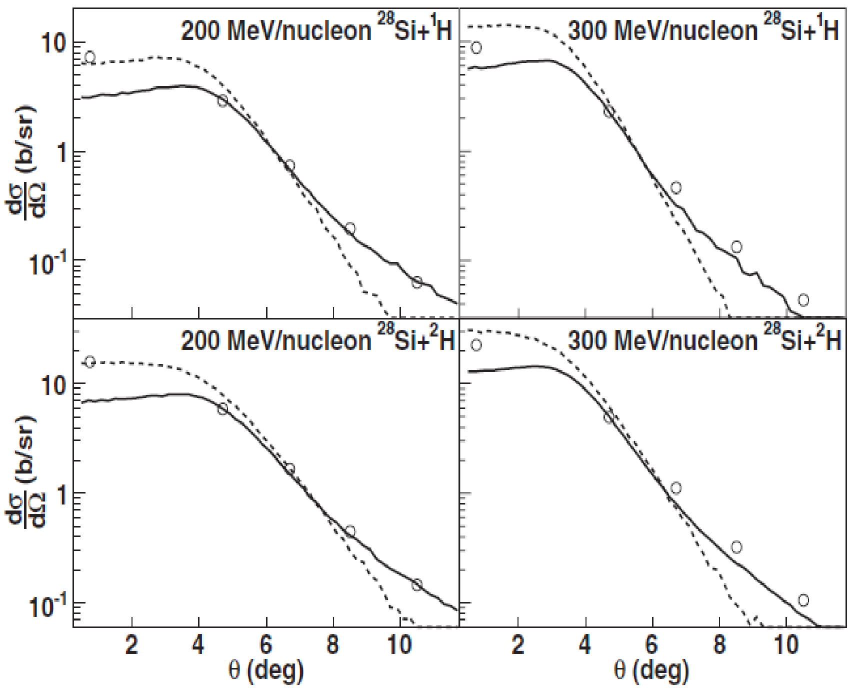
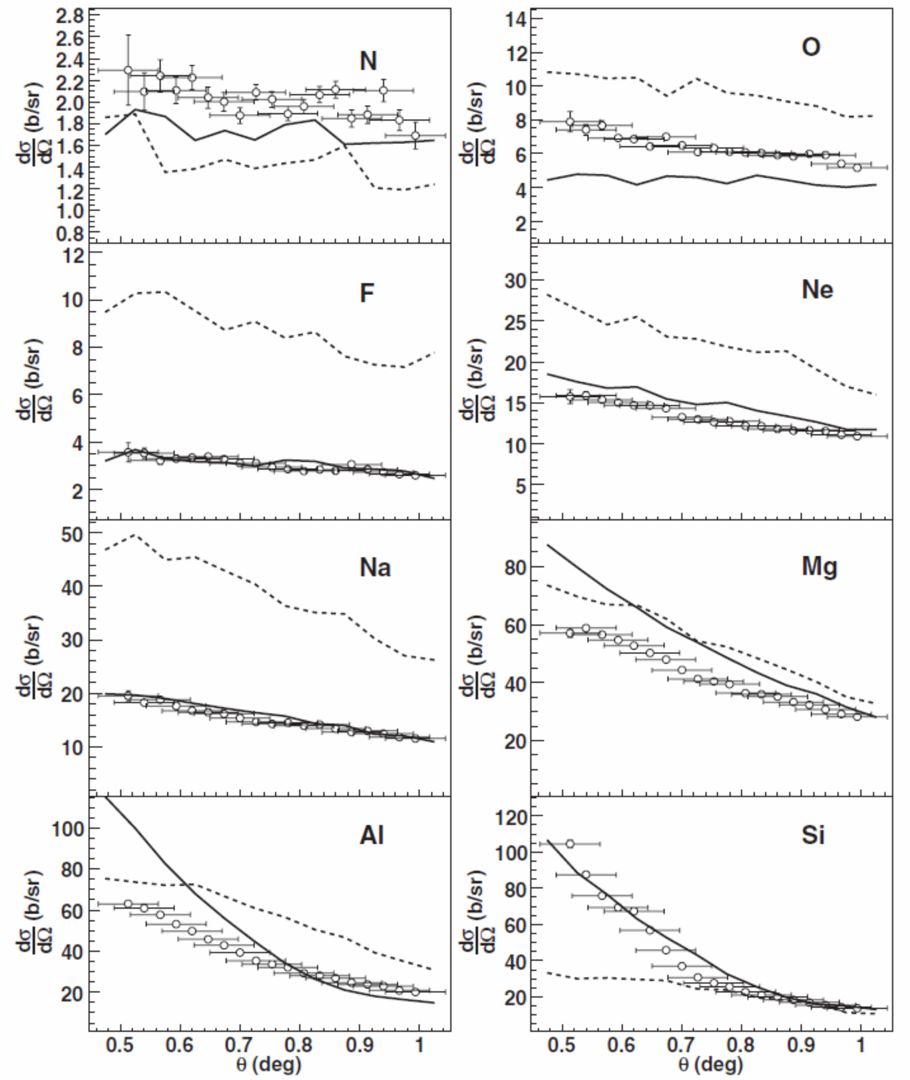
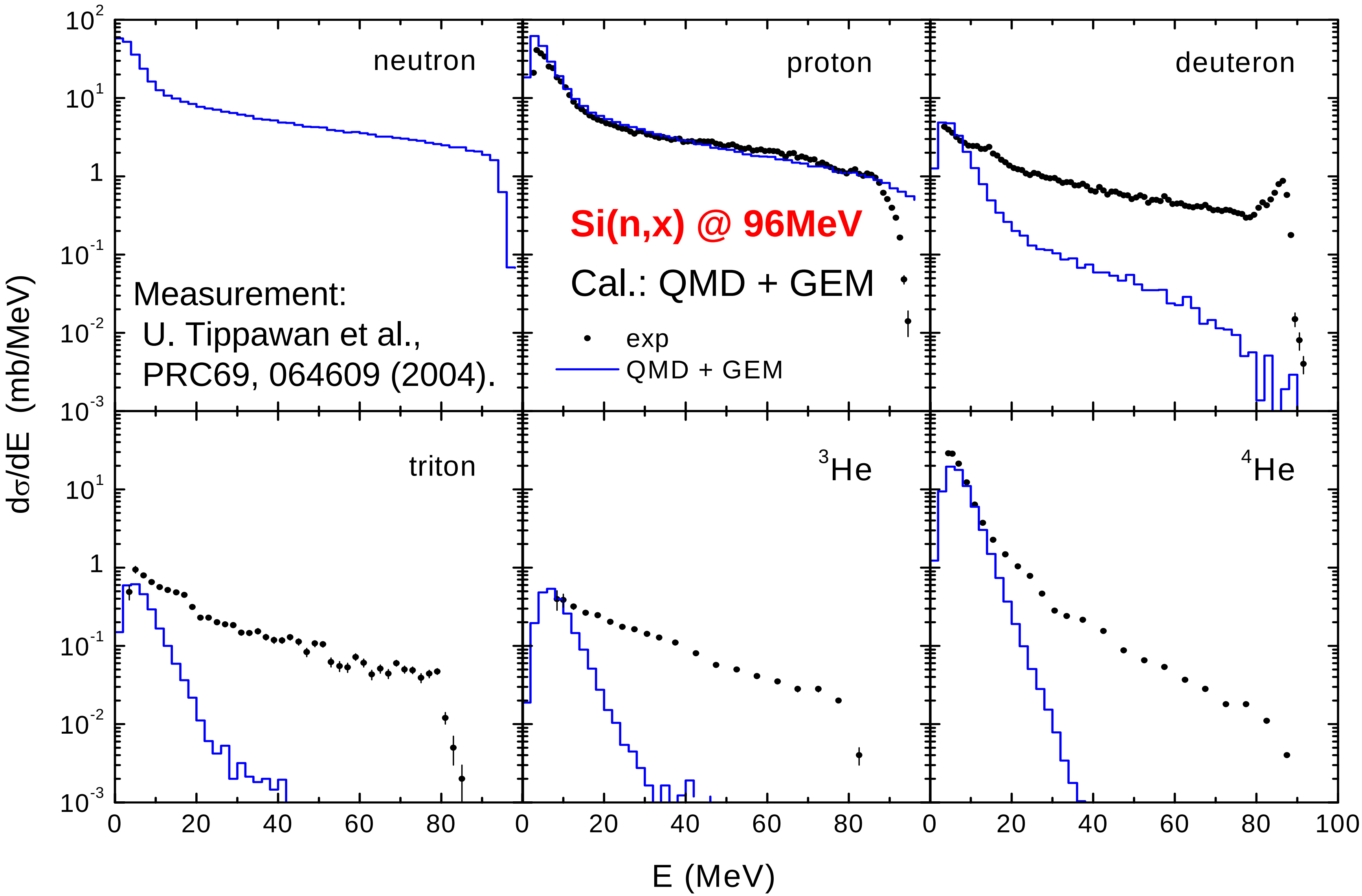


FIG. 2. Angular distribution of He fragments observed with FWD and SAD (open points) for 200 and 300 MeV/nucleon $^{28}Si+^{1}H(^{2}H)$ reactions confronted to the prescription of DCM (solid curves) and JQMD (dashed curves). Statistical error bars fall within the point size.



Present status of QMD for light-ion production

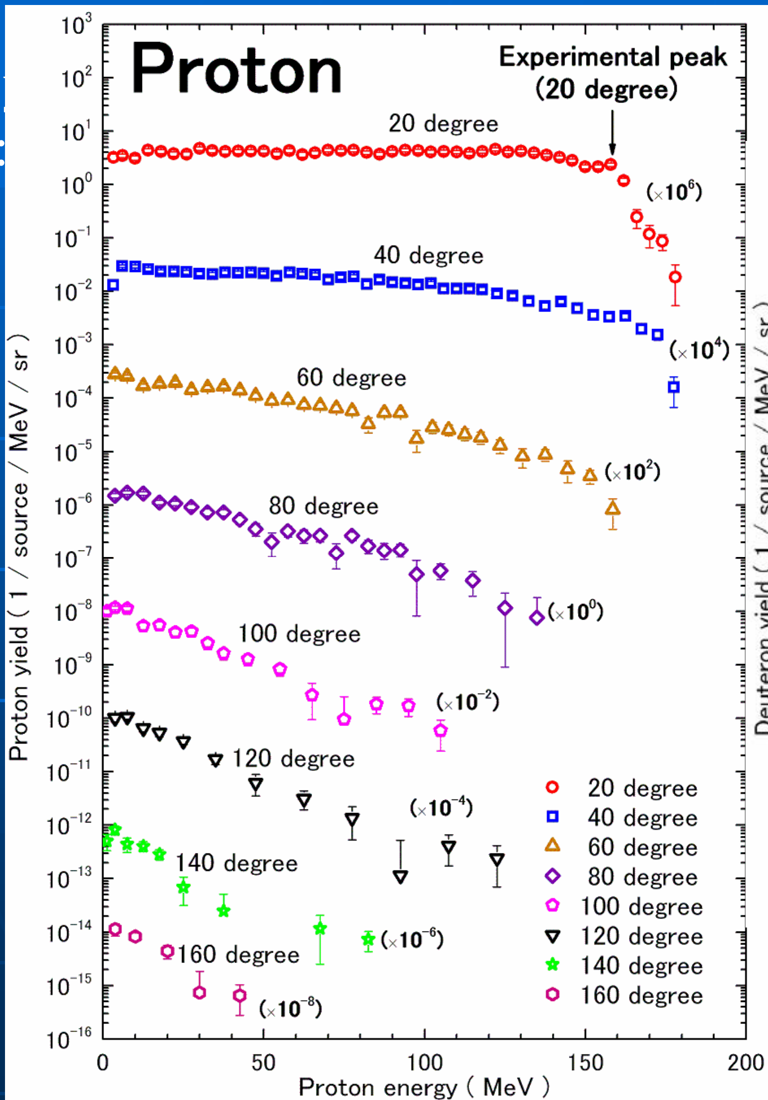


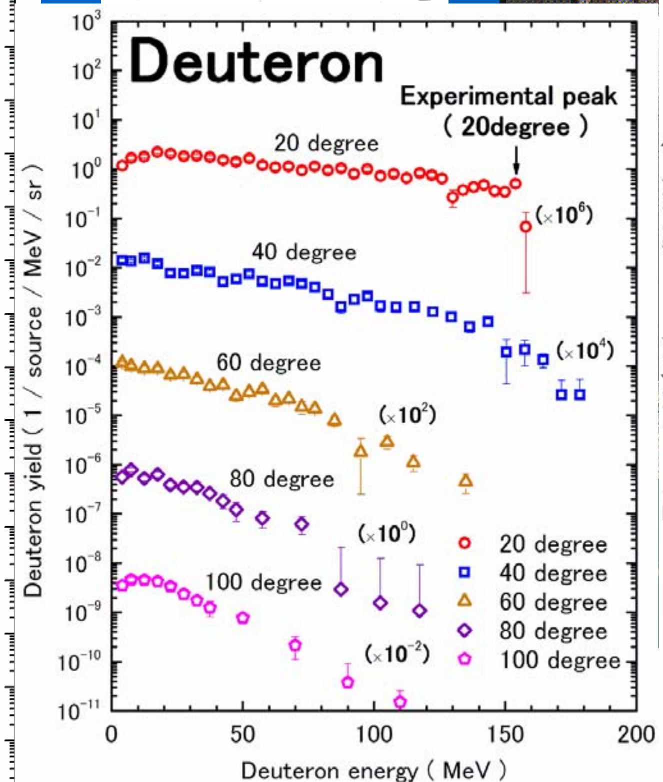
Remarkable underestimation in the preequilibrium region !

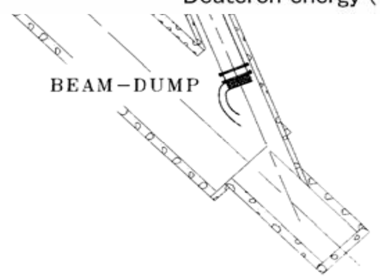
九大-Uppsala大の共同実験

C...
p:...

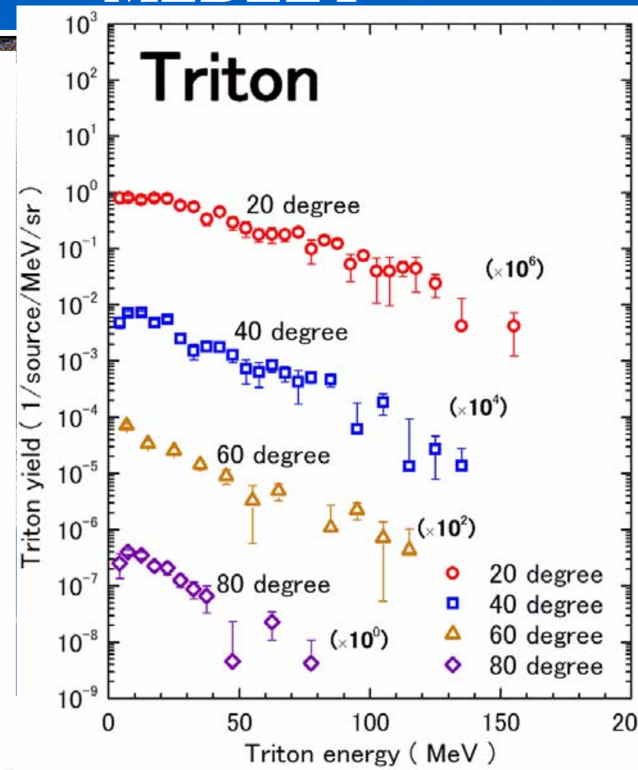
...子発生装置

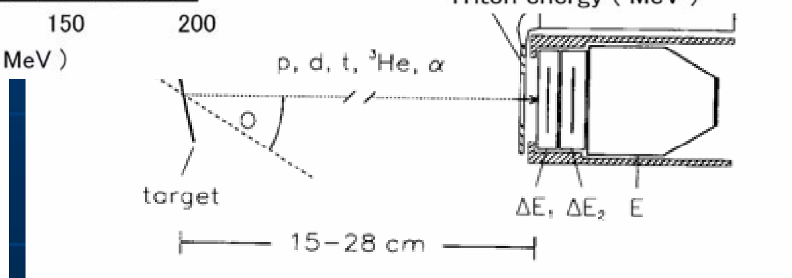






MEDLEY

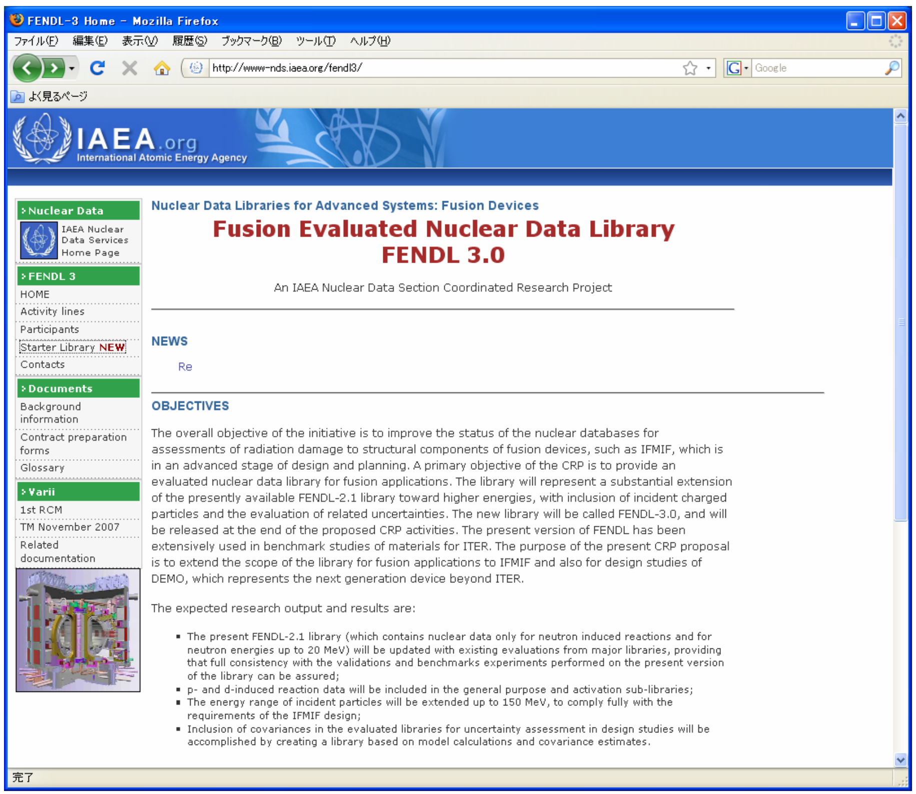




x=p, d, t

核融合炉開発関連トピックス

- FENDL（Fusion Evaluated Nuclear Data Library）
  - ITER, DEMO炉： 20 MeV 中性子データ必要
  - IFMIF： 40MeVまでの重陽子＋50MeVまでの中性子データ


FENDL-3 Home - Mozilla Firefox

ファイル(F) 編集(E) 表示(V) 履歴(S) ブックマーク(B) ツール(T) ヘルプ(H)

http://www-nds.iaea.org/fendl3/

よく見るページ

IAEA.org International Atomic Energy Agency

Nuclear Data
IAEA Nuclear Data Services Home Page

FENDL 3
HOME
Activity lines
Participants
Starter Library NEW
Contacts

Documents
Background information
Contract preparation forms
Glossary

Varii
1st RCM
TM November 2007
Related documentation

Nuclear Data Libraries for Advanced Systems: Fusion Devices

Fusion Evaluated Nuclear Data Library
FENDL 3.0

An IAEA Nuclear Data Section Coordinated Research Project

NEWS

Re

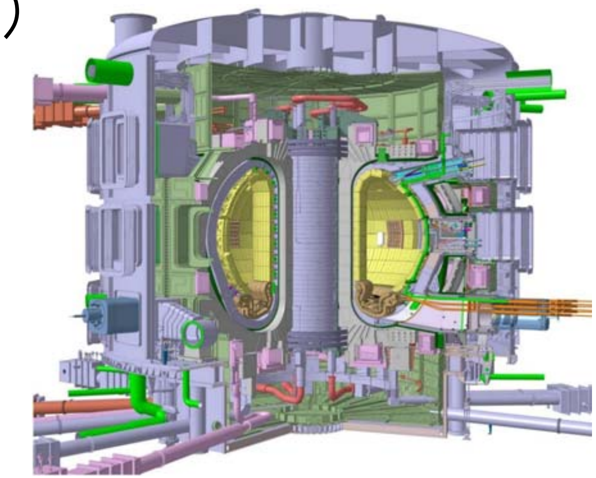
OBJECTIVES

The overall objective of the initiative is to improve the status of the nuclear databases for assessments of radiation damage to structural components of fusion devices, such as IFMIF, which is in an advanced stage of design and planning. A primary objective of the CRP is to provide an evaluated nuclear data library for fusion applications. The library will represent a substantial extension of the presently available FENDL-2.1 library toward higher energies, with inclusion of incident charged particles and the evaluation of related uncertainties. The new library will be called FENDL-3.0, and will be released at the end of the proposed CRP activities. The present version of FENDL has been extensively used in benchmark studies of materials for ITER. The purpose of the present CRP proposal is to extend the scope of the library for fusion applications to IFMIF and also for design studies of DEMO, which represents the next generation device beyond ITER.

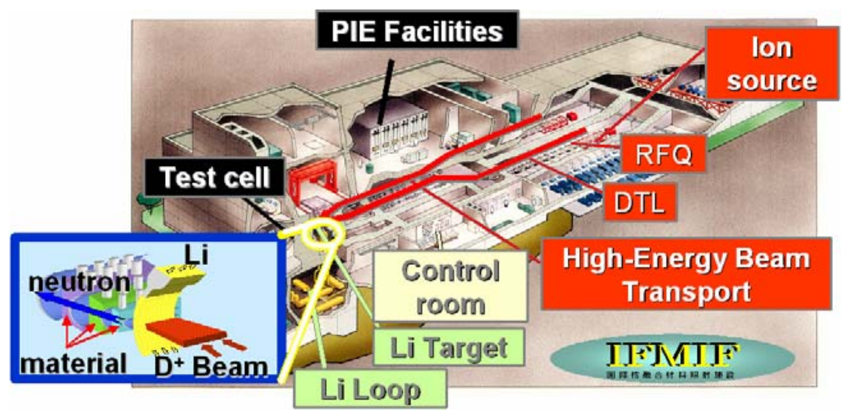
The expected research output and results are:

- The present FENDL-2.1 library (which contains nuclear data only for neutron induced reactions and for neutron energies up to 20 MeV) will be updated with existing evaluations from major libraries, providing that full consistency with the validations and benchmarks experiments performed on the present version of the library can be assured;
- p- and d-induced reaction data will be included in the general purpose and activation sub-libraries;
- The energy range of incident particles will be extended up to 150 MeV, to comply fully with the requirements of the IFMIF design;
- Inclusion of covariances in the evaluated libraries for uncertainty assessment in design studies will be accomplished by creating a library based on model calculations and covariance estimates.

完了



ITER

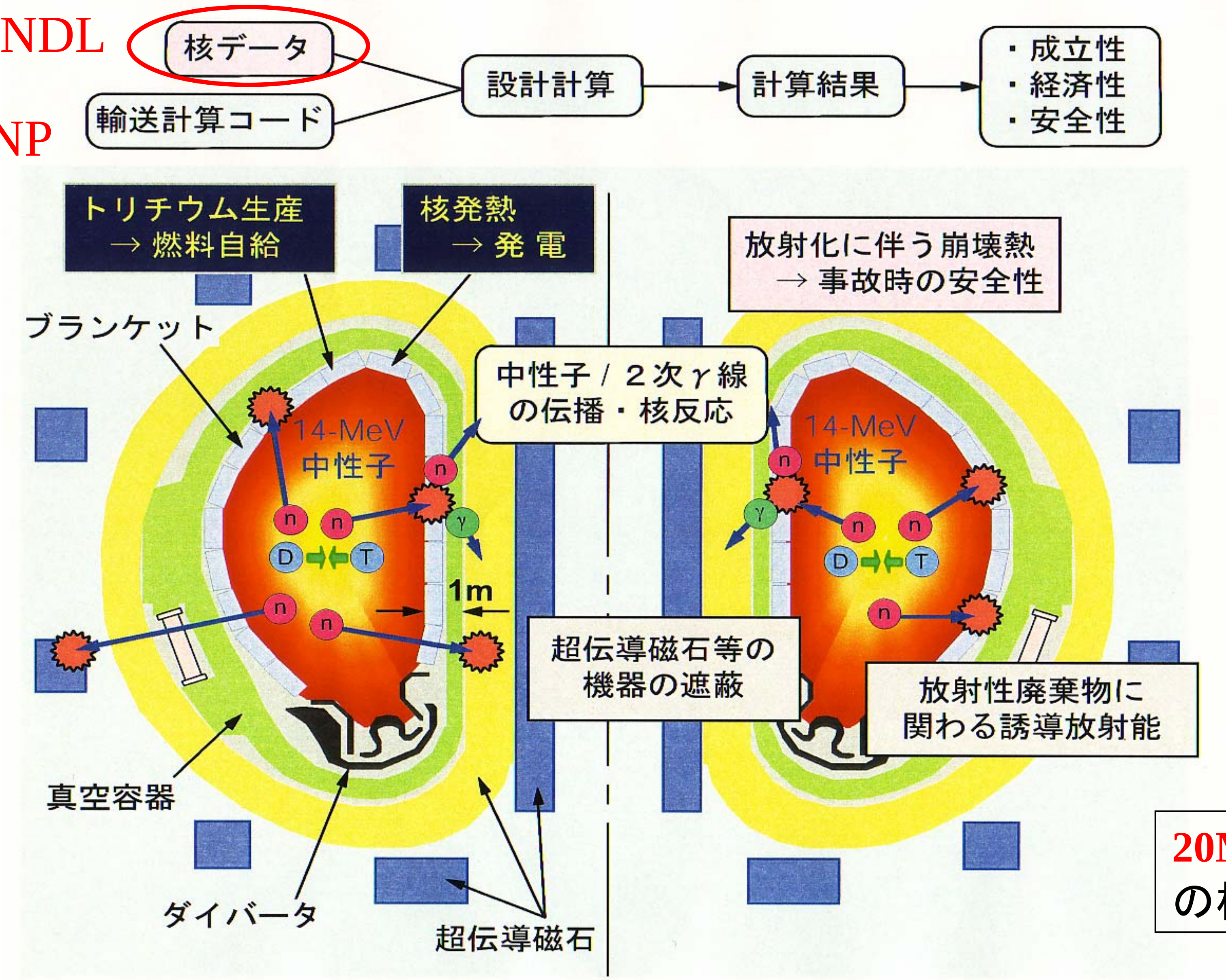


IFMIF

核融合炉ニュートロニクス（中性子工学）

JENDL

MCNP



20MeVまで
の核データ

トリチウムの増殖生産

核融合反応: $D + T \rightarrow He + n + 17.6MeV$

トリチウム生成:
（トリチウム増殖材中）

$^{6}Li + n \rightarrow T + He + 4.8\ MeV$

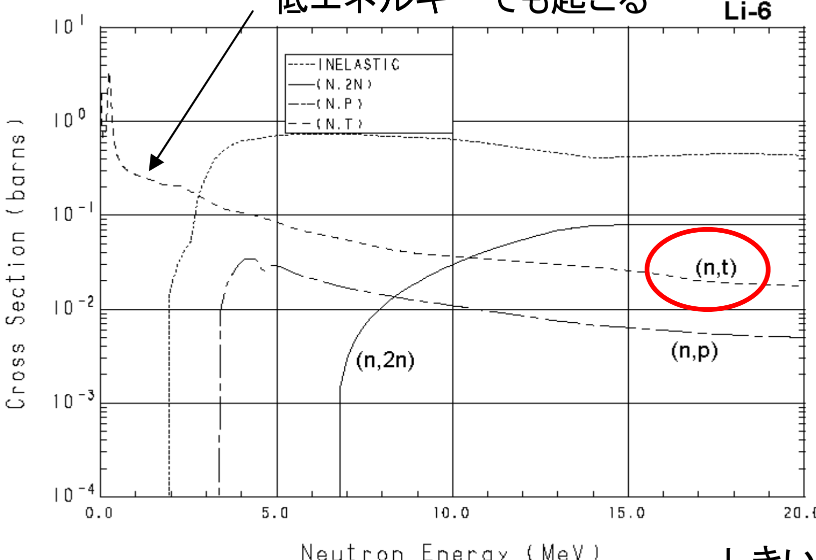
$^{7}Li + n \rightarrow T + He + n' - 2.5\ MeV$

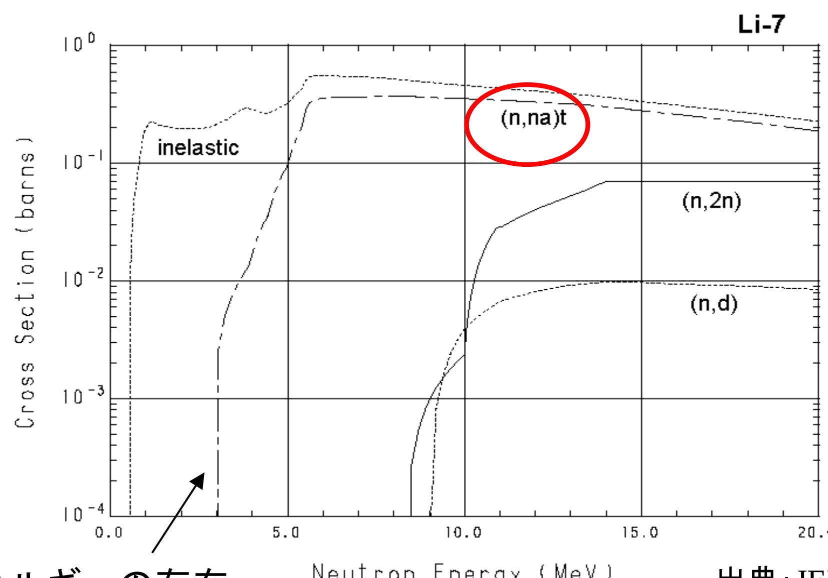
天然リチウム
^{6}Li (7.4%)
^{7}Li (92.6%)

トリチウム増殖比 (TBR) = 生成されるT／消費されるT

TBR > ～1.1要求

低エネルギーでも起こる





しきいエネルギーの存在

出典:JENDL-3.2

中性子増倍反応:

$^{9}Be + n \rightarrow 2n + 2He - 2.5\ MeV$

$^{A}Pb + n \rightarrow 2n + ^{A-1}Pb - 7\ MeV$

中性子による材料損傷

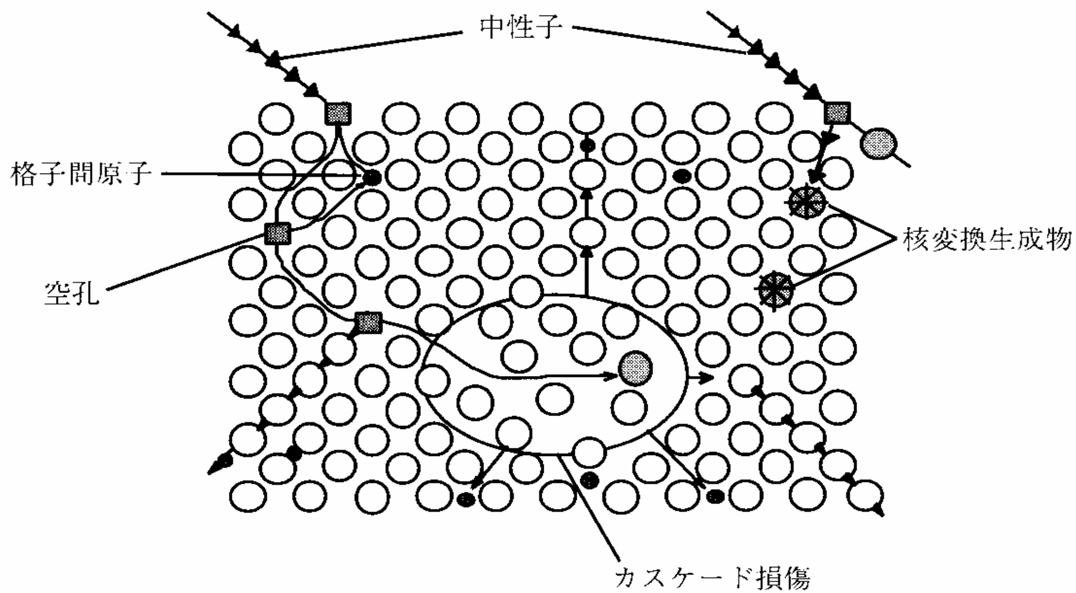


図 11.1　材料損傷の素過程

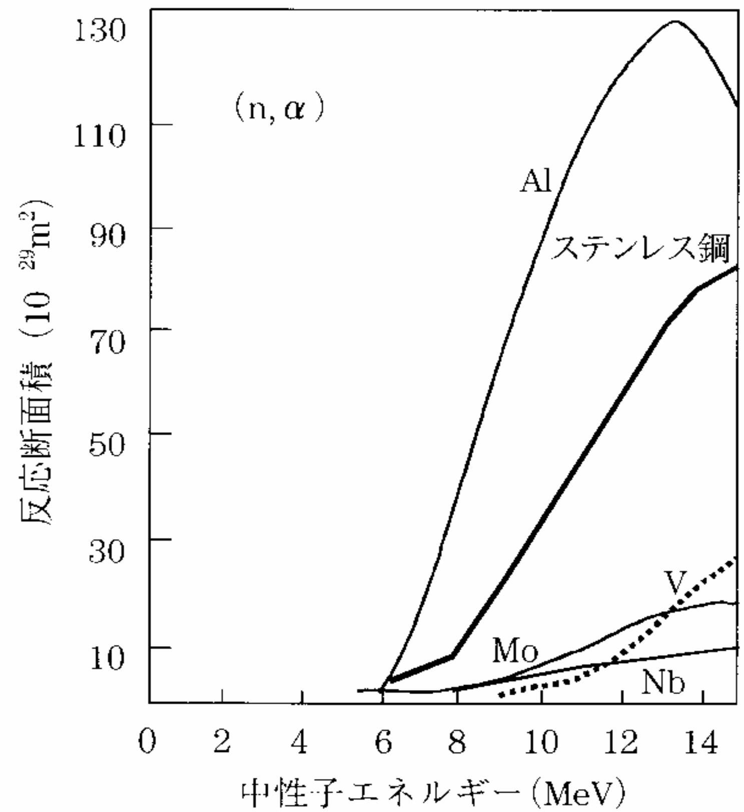
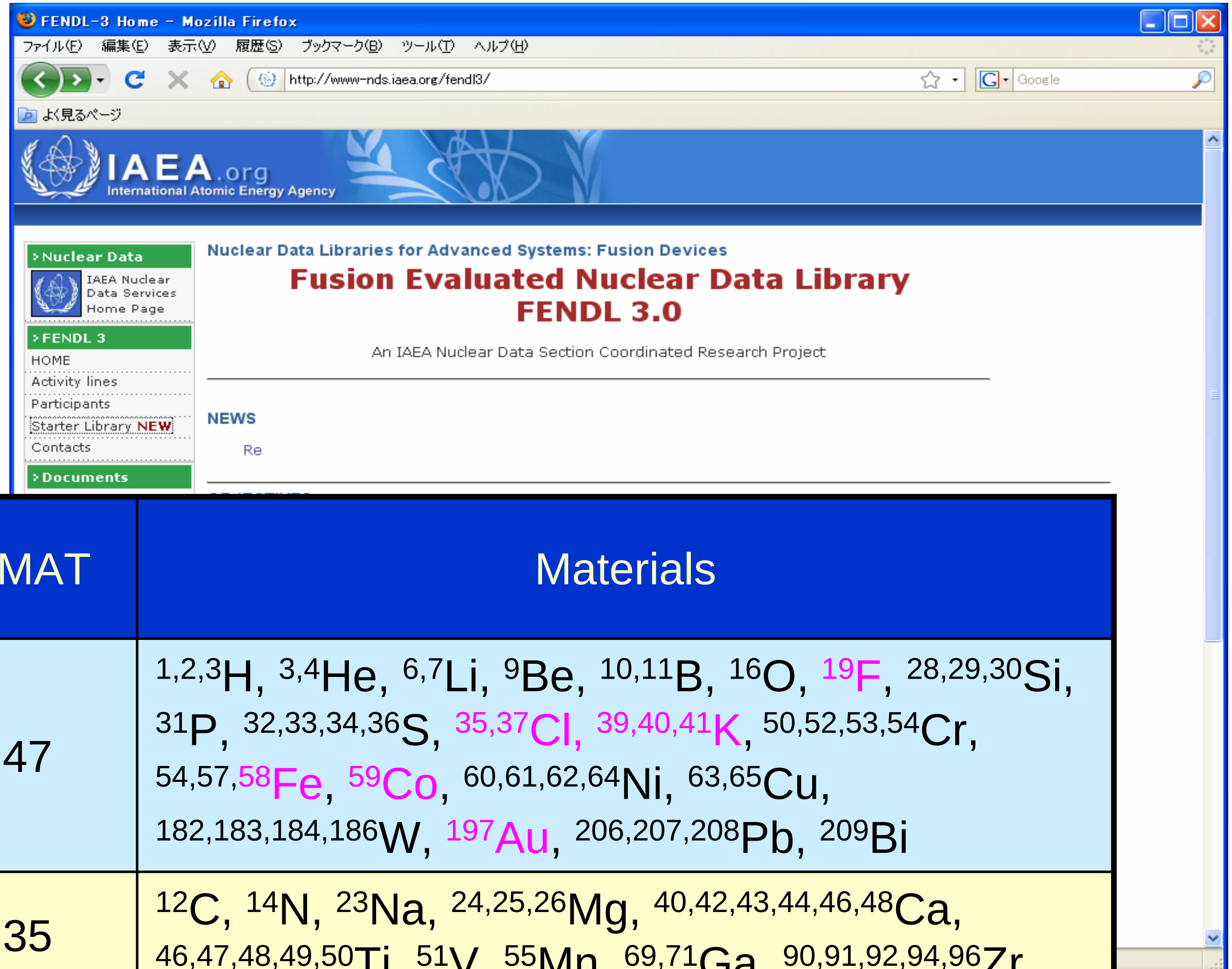


図 11.2　反応断面積の中性子エネルギー依存性（出典：E. Teller: "Fusion", vol.1, Magnetic Confinement part B, 1881, Academic Press, New York.）

引用：関昌弘著、核融合炉工学概論

FENDL-3

- Up to 150 MeV
- n, p, d



No.	Library	NMAT	Materials
1	ENDF/B-VII.0	47	^{1,2,3}H, ^{3,4}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{16}O, ^{19}F, ^{28,29,30}Si, ^{31}P, ^{32,33,34,36}S, ^{35,37}Cl, ^{39,40,41}K, ^{50,52,53,54}Cr, ^{54,57,58}Fe, ^{59}Co, ^{60,61,62,64}Ni, ^{63,65}Cu, ^{182,183,184,186}W, ^{197}Au, ^{206,207,208}Pb, ^{209}Bi
2	JENDL/HE-2007	35 (+11)	^{12}C, ^{14}N, ^{23}Na, ^{24,25,26}Mg, ^{40,42,43,44,46,48}Ca, ^{46,47,48,49,50}Ti, ^{51}V, ^{55}Mn, ^{69,71}Ga, ^{90,91,92,94,96}Zr, ^{93}Nb, ^{92,94,95,96,97,98,100}Mo, ^{181}Ta,
3	JEFF-3.1	4	^{27}Al, ^{56}Fe, ^{58,60}Ni
4	BROND-2	2	^{15}N, ^{nat}Sn

FENDL-3.0 Starter File (88 nuclides)

#)	MAT	Material	Lab.	Date	Authors	Source
1)	125	1-H-1	LANL	EVAL-OCT05	G.M.Hale	ENDF/B-VII
2)	128	1-H-2	LANL	EVAL-FEB97	P.G.Young,G.M.Hale,M.B.Chadwick	ENDF/B-VII
3)	131	1-H-3	LANL	EVAL-NOV01	G.M.Hale	ENDF/B-VII
4)	225	2-He-3	LANL	EVAL-MAY90	G.Hale,D.Dodder,P.Young	ENDF/B-VII
5)	228	2-He-4	LANL	EVAL-OCT73	Nisley,Hale,Young	ENDF/B-VII
6)	325	3-Li-6	LANL	EVAL-APR06	G.M.Hale, P.G.Young	ENDF/B-VII
7)	328	3-Li-7	LANL	EVAL-AUG88	P.G.Young	ENDF/B-VII
8)	425	4-Be-9	LLNL,LANL	EVAL-JAN86	Perkins,Plechaty,Howerton,Frankle	ENDF/B-VII
9)	525	5-B-10	LANL	EVAL-APR06	G.M.Hale,P.G.Young	ENDF/B-VII
10)	528	5-B-11	LANL	EVAL-MAY89	P.G.Young	ENDF/B-VII
11)	625	6-C-12	Kyushu U.	EVAL-JUL03	Y. Watanabe	JENDL-HE
12)	720	7-N-15	CJD	EVAL-APR89	A.I.BLOKHIN, N.S.RABOTNOV	BROND-2
13)	725	7-N-14	AITEL	EVAL-MAY05	T.Murata, K.kosako and T.Fukahori	JENDL-HE
14)	825	8-O-16	LANL	EVAL-DEC05	Hale,Young,Chadwick,Caro,Lubitz	ENDF/B-VII
15)	925	9-F-19	CNDC,ORNL	EVAL-OCT03	Z.X.Zhao,C.Y.Fu,D.C.Larson, Leal+	ENDF/B-VII
16)	1125	11-NA-23	SIT.SHIMZ	EVAL-MAY 6	K. Kosako	JENDL-HE
17)	1225	12-MG-24	KYUSHU	EVAL-DEC 3	Sun Weili and Y.Watanabe	JENDL-HE
18)	1228	12-MG-25	KYUSHU	EVAL-DEC 3	Sun Weili and Y.Watanabe	JENDL-HE
19)	1231	12-MG-26	KYUSHU	EVAL-DEC 3	Sun Weili and Y.Watanabe	JENDL-HE
20)	1325	13-Al-27	LANL	EVAL-FEB97	M.B.CHADWICK & P.G.YOUNG	JEFF-31
21)	1425	14-Si-28	LANL,ORNL	EVAL-DEC02	M.B.Chadwick,P.G.Young,D.Hetrick	ENDF/B-VII
22)	1428	14-Si-29	LANL,ORNL	EVAL-JUN97	M.B.Chadwick,P.G.Young,D.Hetrick	ENDF/B-VII
23)	1431	14-Si-30	LANL,ORNL	EVAL-JUN97	M.B.Chadwick,P.G.Young,D.Hetrick	ENDF/B-VII
24)	1525	15-P-31	LANL,LLNL	EVAL-DEC97	M.Chadwick,P.Young,R.Howerton	ENDF/B-VII
25)	1625	16-S-32	FUJI E.C.	EVAL-MAY87	H.Nakamura	ENDF/B-VII
26)	1628	16-S-33	FUJI E.C.	EVAL-MAY87	H.Nakamura	ENDF/B-VII
27)	1631	16-S-34	FUJI E.C.	EVAL-MAY87	H.Nakamura	ENDF/B-VII
28)	1637	16-S-36	FUJI E.C.	EVAL-MAY87	H.Nakamura	ENDF/B-VII
29)	1725	17-Cl-35	ORNL,LANL	EVAL-OCT03	Sayer,Guber,Leal,Larson,Young+	ENDF/B-VII
30)	1731	17-Cl-37	ORNL,LANL	EVAL-OCT03	Sayer,Guber,Leal,Larson,Young+	ENDF/B-VII
31)	1925	19-K-39	FUJI E.C.	EVAL-MAY87	H.Nakamura	ENDF/B-VII
32)	1928	19-K-40	FUJI E.C.	EVAL-MAY87	H.Nakamura	ENDF/B-VII
33)	1931	19-K-41	FUJI E.C.	EVAL-MAY87	H.Nakamura	ENDF/B-VII
34)	2025	20-CA-40	SAEI	EVAL-MAY 3	K. Kosako	JENDL-HE
35)	2031	20-CA-42	SAEI	EVAL-MAY 3	K. Kosako	JENDL-HE
36)	2034	20-CA-43	SAEI	EVAL-MAY 3	K. Kosako	JENDL-HE
37)	2037	20-CA-44	SAEI	EVAL-MAY 3	K. Kosako	JENDL-HE
38)	2043	20-CA-46	SAEI	EVAL-MAY 3	K. Kosako	JENDL-HE
39)	2049	20-CA-48	SAEI	EVAL-MAY 3	K. Kosako	JENDL-HE

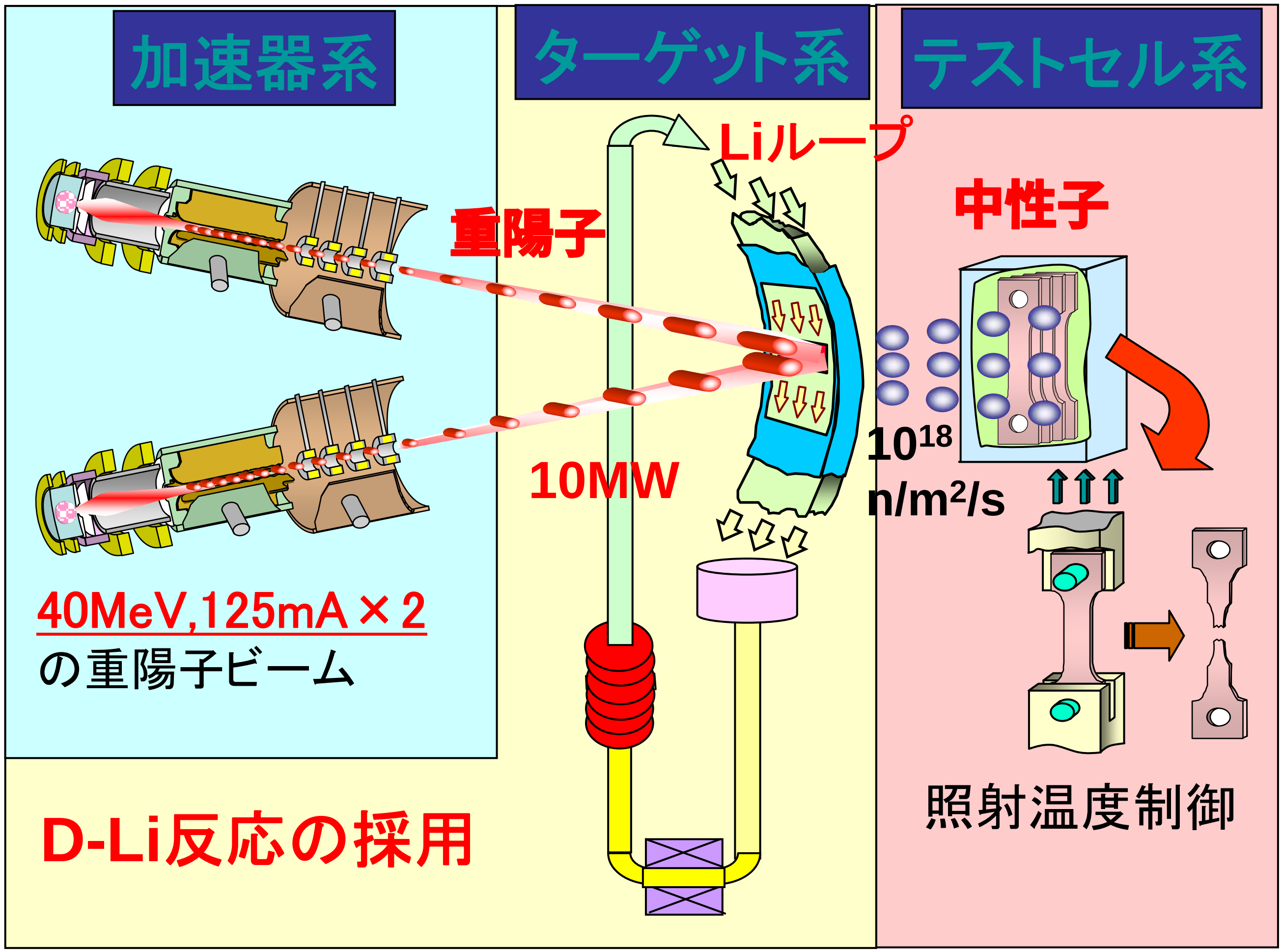
20MeV 以上無 (rows 3)–11))

20MeV 以上 TENDL-2008 (rows 25)–28))

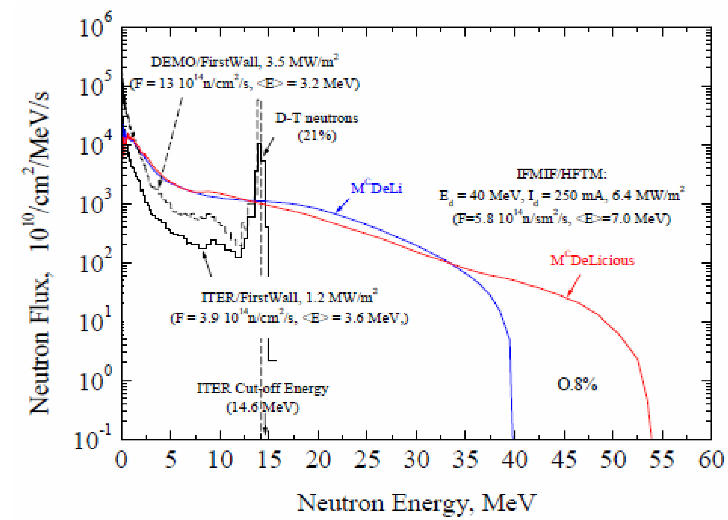
20MeV 以上 JENDL-HE (rows 29)–33))

Deuteron Induced Reaction

IFMIF (International Fusion Materials Irradiation Facility)



中性子エネルギー分布



参考文献：

- 日本原子力学会誌, Vol. 49, No.4 (2007), pp. 267
- プラズマ・核融合学会誌, Vol.82, (2006), pp.3

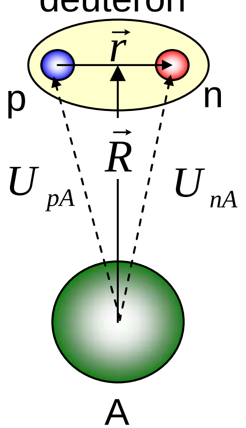
CDCC analysis of d+Li reactions

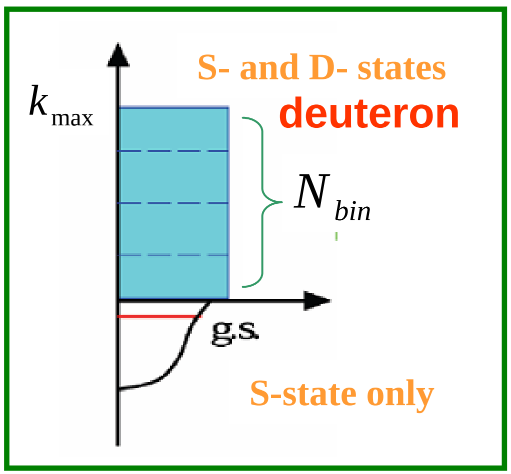
Application of **the CDCC method** to deuteron elastic scattering from ^{6,7}Li

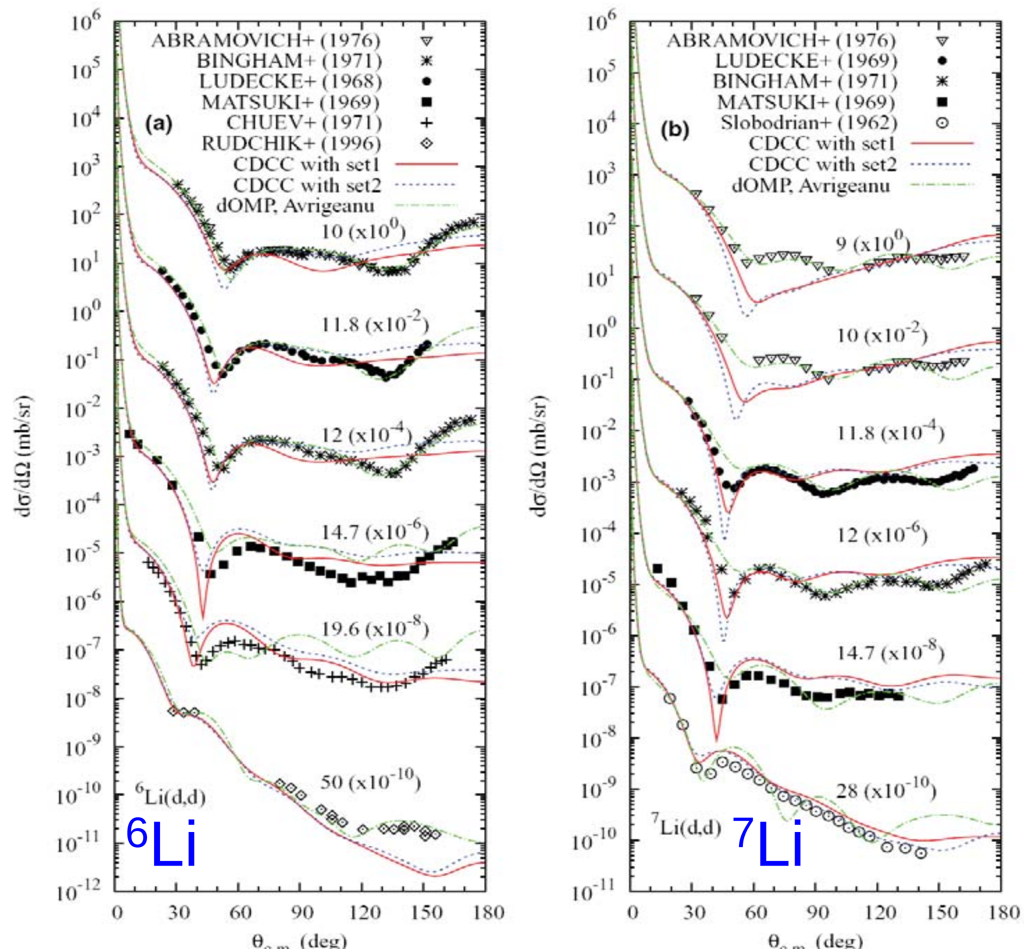
T. Ye, Y. Watanabe, K. Ogata, and S. Chiba, PRC 78, 024611 (2008).

The **CDCC** (**C**ontinuum **D**iscretaized **C**oupled-**C**hannels) method describes deuteron breakup process (A+2 body system) with following phenomenological three-body Hamiltonian :

$$H_{eff} = T_R + U_{pA}(\vec{r}_p, \vec{s}_p, E_d/2) + U_{nA}(\vec{r}_n, \vec{s}_n, E_d/2) + V_p^{(Coul)}(R) + H_{pn}(\vec{r}, \vec{s}_p, \vec{s}_n)$$



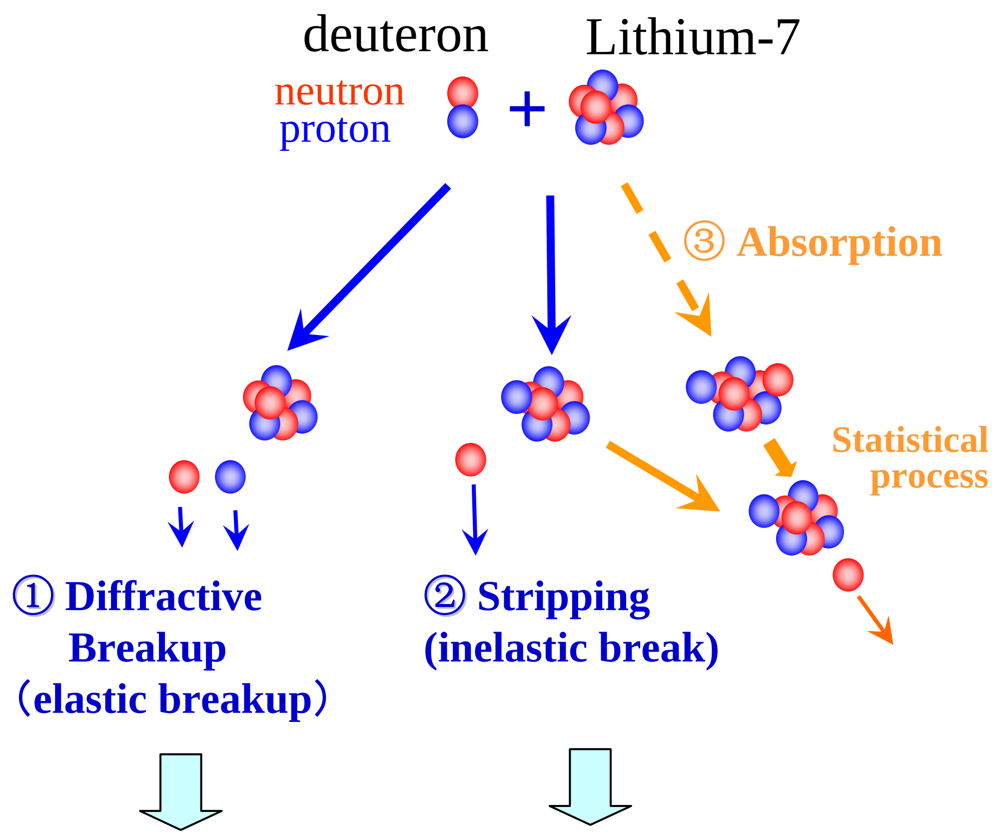




Code: CDCDEU+HICADEU (by Y. Iseri et al.)

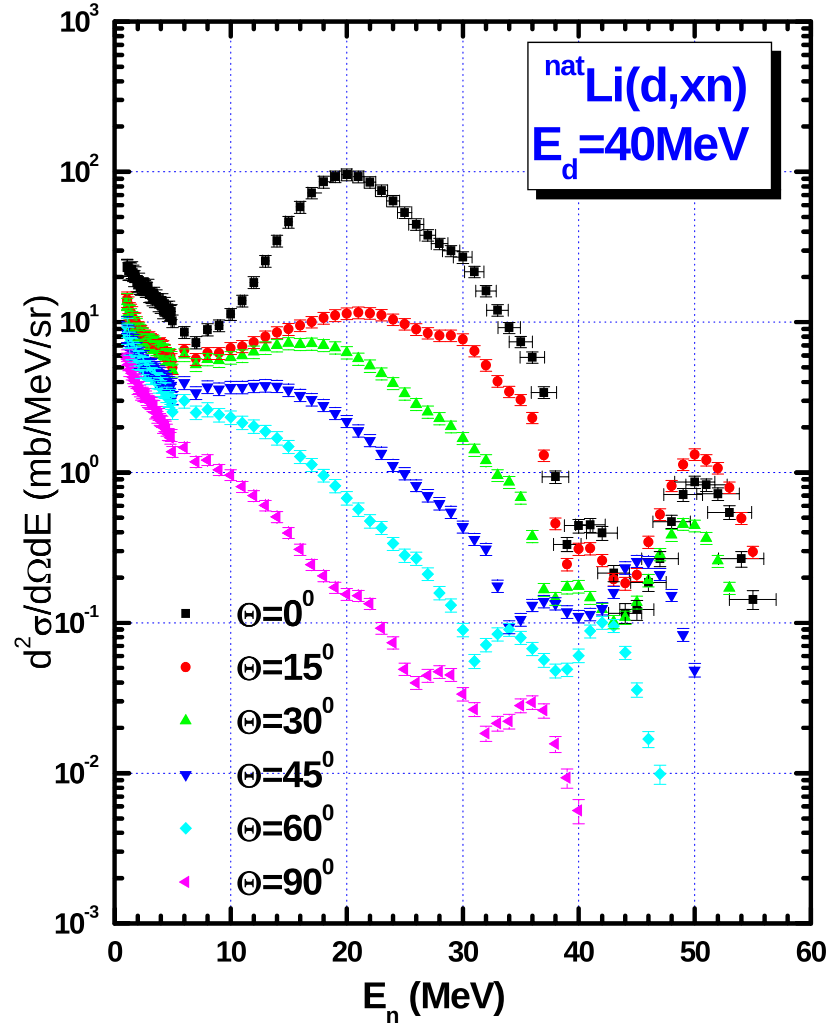
CDCC+Glauber analysis of Li(d,nx) reactions

Schematic view of neutron production



CDCC
S-matrices for d-breakup transition

Glauber model
(eikonal approx. + adiabatic approx.)



Ref.) Exp. data:
M. Hagiwara, *el at.*, Fus. Sci. Tech. 48, 1320 (2005).

まとめ

- データの完備性：
  - ✓ 2次生成粒子・反跳イオンの全断面積およびエネルギー・角度分布
  - ✓ 全放出エネルギー・角度範囲に亘るデータ
- Exclusiveデータの必要性（放出粒子間相関）
  - ✓ シングルイベント現象（半導体や細胞）
  - ✓ データベースでなく、event generator（モンテカルロ法）で対応
- 核子入射ばかりでなく、複合粒子も必要（例：重陽子）
- 軽核（1p殻核：Li, Be, B, C, N, O）の断面積評価が課題

- 計算コード・サブルーチンの公開とライブラリ化