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1930-1

Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions

4 - 8 February 2008

Experimental Cross Sections for the Production of Residual Nuclides at Medium Energies.

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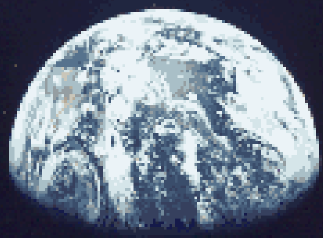

Experimental Cross Sections for the Production of Residual Nuclides at Medium Energies:

Status, Recent Progress, and Challenges for Modeling

R. Michel,
D. Hansmann, Shams A.M. Issa, M. Tutuc

Joint ICTP-IAEA Advanced Workshop on Model Codes for Spallation Reactions,
Trieste / February 4 – 8, 2008

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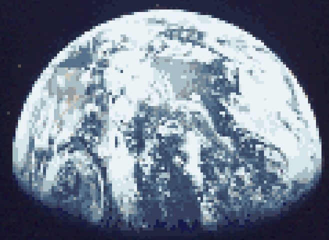

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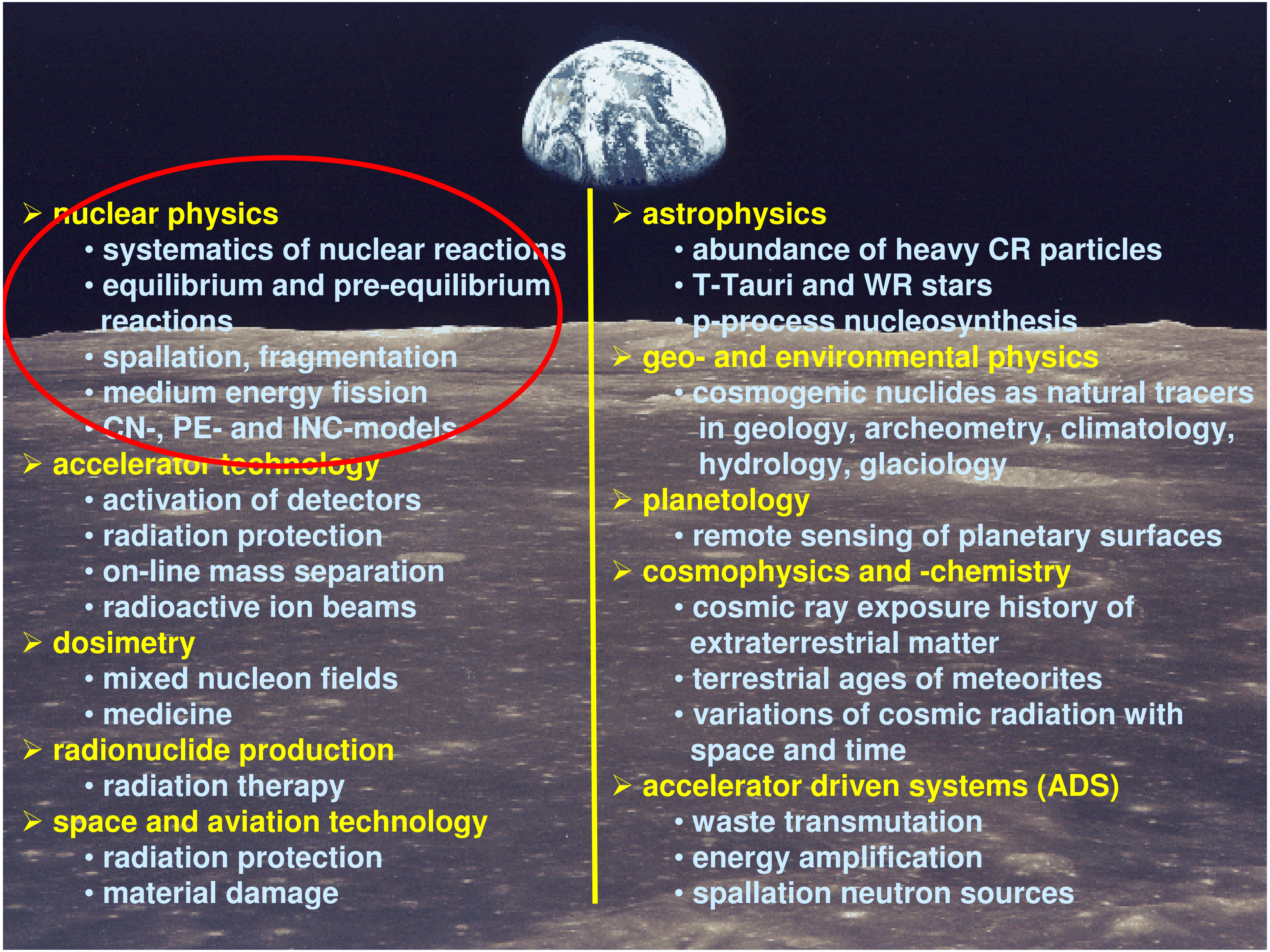
➢ nuclear physics
• systematics of nuclear reactions
• equilibrium and pre-equilibrium reactions
• spallation, fragmentation
• medium energy fission
• CN-, PE- and INC-models
➢ accelerator technology
• activation of detectors
• radiation protection
• on-line mass separation
• radioactive ion beams
➢ dosimetry
• mixed nucleon fields
• medicine
➢ radionuclide production
• radiation therapy
➢ space and aviation technology
• radiation protection
• material damage
➢ astrophysics
• abundance of heavy CR particles
• T-Tauri and WR stars
• p-process nucleosynthesis
➢ geo- and environmental physics
• cosmogenic nuclides as natural tracers in geology, archeometry, climatology, hydrology, glaciology
➢ planetology
• remote sensing of planetary surfaces
➢ cosmophysics and -chemistry
• cosmic ray exposure history of extraterrestrial matter
• terrestrial ages of meteorites
• variations of cosmic radiation with space and time
➢ accelerator driven systems (ADS)
• waste transmutation
• energy amplification
• spallation neutron sources

Production Rate P_i of a Residual Nuclide i at Medium Energies

$$P_i\left(d, R, \vec{c}_s, \vec{c}_b\right) = N_L \cdot \sum_j \frac{c_{s,j}}{A_j} \cdot \sum_k \int_0^\infty \sigma_{i,j,k}(E_k) \cdot J_k(E_k, d, R, \vec{c}_b)\, \mathrm{d}E_k$$

- depth in the target
- size of the target
- sample chemistry
- bulk target chemistry
- target elements
- particle types
- cross sections
- spectral fluences

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Production of Residual Nuclides by Intermediate-Energy Particles

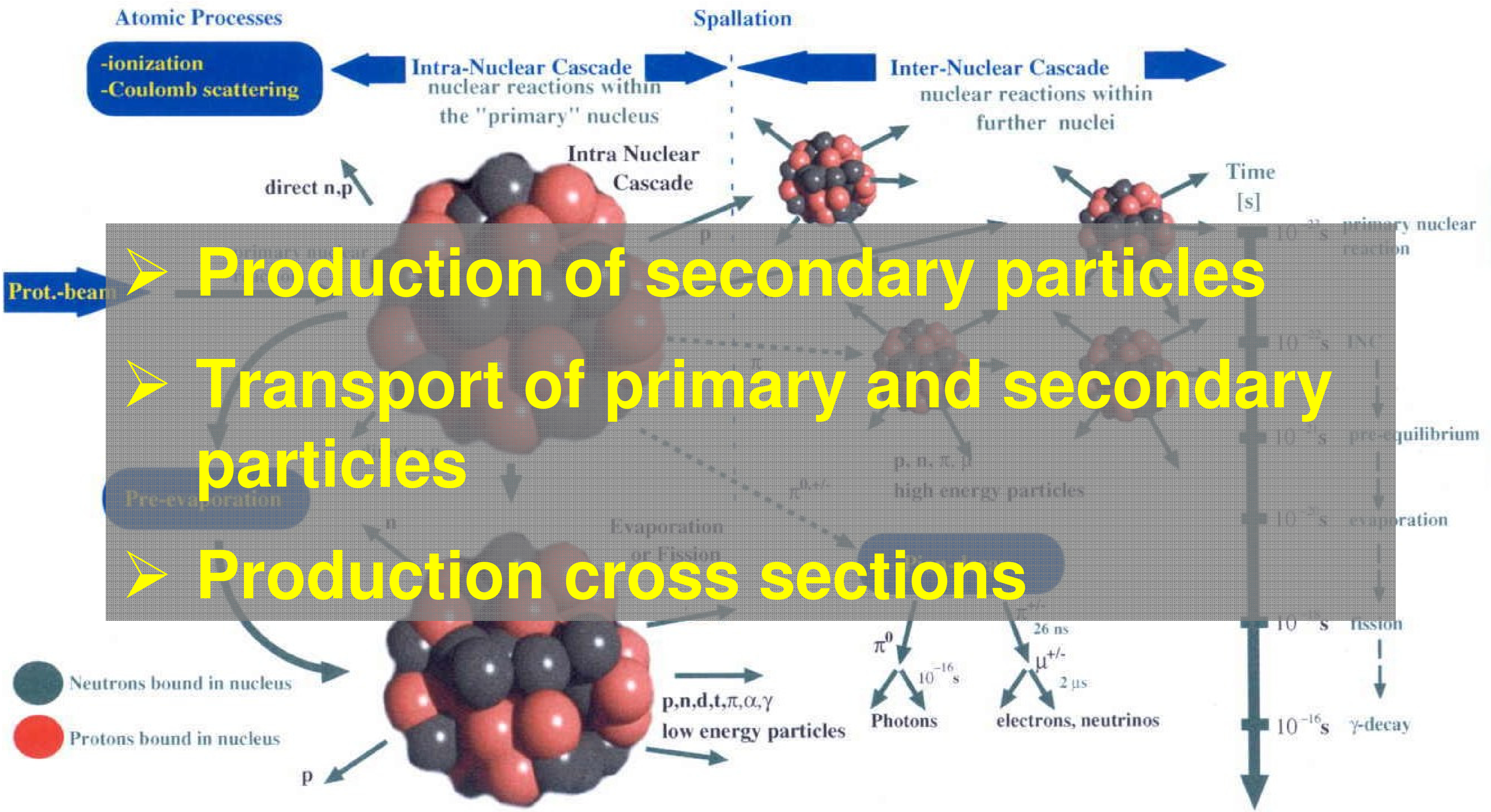
primary particles: p, ^{4}He
secondary particles: p, n, ^{2}H, ^{3}H, ^{3}He, ^{4}He, ...

up to 200 MeV/A: secondary particles negligible
> 200 MeV up to 10 GeV/A: secondary particles dominant

Ockham's razor: Use as few particle types as possible!

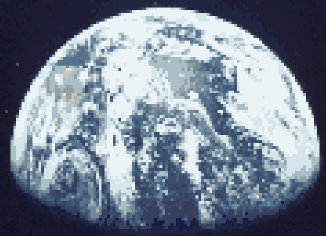
relevant energies: 1 MeV - 10 GeV for protons
1 meV - 200 MeV for neutrons

Essentials of Modeling Residual Nuclide Production at Intermediate Energies



- Production of secondary particles
- Transport of primary and secondary particles
- Production cross sections

Contents



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- conclusions

Specification of the 1997 NEA International Codes and Model Intercomparison for Intermediate Energy Activation Yields

O-16 Be-7, Be-10, C-11, C-14

Al-27 H-3, He-3, He-4, Be-7, Be-10, Na-22 (Mg-22), Na-24 (Ne-26), (Si-26)

Fe (nat) H-3, He-3, He-4, Be-7, Be-10, Ne-20 (all mass 20 nuclides), Ne-21 (all mass 21 nuclides),Ne-22 (F-22), Na-22 (Mg-22), Na-24 (Ne-24), Mg-28 (Na-28), Al-26 (Si-26), Cl-36, Ar-36 (K-36, Ca-36), Ar-38 (all mass 38 nuclides), Sc-46, V-48 (Cr-48), Cr-51 (Mn-51, Fe-51),Mn-52m+g (Fe-52), Mn-53 (Fe-53, Co-53), Mn-54, Fe-55 (Co-55, Ni-55), Co-56

Co-59 Co-56, Co-57, Co-58, Ni-56, Ni-57

Zr (nat) Be-7, Na-22 (Mg-22), Sc-46, V-48, (Cr-48)), Cr-51 (Mn-51, Fe-51), Mn-54, Co-56 (Ni-56),Co-58, Co-60, Zn-65 (Ga-65, Ge-65), Ga-67 (Ge-67, As-67), Ge-69 (As-69, Se-69), As-71(Se-71, Br-71, Kr-71) As-74, Se-75 (Br-75, Kr-75, Rb-75), Br-77 (Kr-77, Rb-77, Sr-77), Kr-78(Br-78, Rb-78), Kr-79 (Rb-79, Sr-79), Kr-80 (Br-80, Rb-80, Sr-80, Y-80), Kr-81 (Rb-81, Sr-81,Y-81, Zr-81), Kr-82 (Br-82, Rb-82, Sr-82, Y-82, Zr-82), Kr-83 (all mass 83 nuclides), Kr-84(Br-84, Se-84, Rb-84), Kr-85 (Se-85, Br-85), Kr-86 (Se-86, Br-86, Rb-86), Rb-83 (Sr-83, Y-83, Zr-83), Rb-84, Rb-86, Sr-82 (Y-82, Zr-82), Sr-83 (Y-83, Zr-83), Sr-85 (Y-85, Zr-85, Nb-85), Y-86 (Zr-86, Nb-86), Y-86m, Y-87 (Zr-87, Nb-87), Y-87m, Y-88 (Zr-88, Nb-88), Zr-86(Nb-86), Zr-88 (Nb-88), Zr-89 (Nb-89), Zr-95 (Y-95), Nb-90, Nb-92m, Nb-95, Nb-95m, Nb-96

Au-197 Be-7, Na-22 (Mg-22), Na-24 (Ne-24), Sc-46, V-48 (Cr-48), Mn-54, Fe-59 (Mn-59), Co-56 (Ni-56), Co-58, Co-60, Zn-65 (Ga-65, Ge-65), As-74, Se-75 (Br-75, Kr-75, Rb-75), Rb-83 (Sr-83,Y-83, Zr-83), Rb-84, Rb-86, Sr-85 (Y-85, Zr-85, Nb-85), Y-87 (Zr-87, Nb-87), Y-88 (Zr-88, Nb-88), Zr-88 (Nb-88), Zr-89 (Nb-89), Zr-95 (Y-95), Nb-95 (Rb-95, Sr-95, Y-95, Zr-95), Tc-96,Ru-103 (Nb-103, Mo-103, Tc-103), Rh-102, Ag-105 (Cd-105, In-105), Ag-110m, Ag-110,Sn-113 (Sb-113, Te-113, I-113, Xe-113), Te-121 (I-121, Xe-121, Cs-121, Ba-121), Te-121m,Te-121m+g, Xe-127 (Cs-127, Ba-127, La-127), Ba-131 (La-131, Ce-131), Ce-139 (Pr-139,Nd-139, Pm-139, Sm-139), Eu-145 (Gd-145), Eu-147 (Gd-147, Tb-147), Eu-148, Eu-149 (Gd-149, Tb-149, Dy-149, Ho-149), Gd-146 (Tb-146), Gd-147 (Tb-147, Dy-147), Gd-149 (Tb-149,Dy-149, Ho-149), Gd-151 (Tb-151, Dy-151, Ho-151), Gd-153 (Tb-153, Dy-153, Ho-153),Tb-149 (Dy-149, Ho-149), Tb-151 (Dy-151, Ho-151), Tb-153 (Dy-153, Ho-153), Tm-165 (Y-165, Lu-165, Hf-165), Tm-166 (Y-166, Lu-166, Hf-166, Ta-166, W-166), Tm-167 (Y-167, Hf-167, Ta-167), Tm-168, Yb-166 (lu-166, Hf-166, Ta-166), Yb-169 (Lu-169, Hf-169, Ta-169) ,Lu-169 (Hf-169, Ta-169), Lu-170 (Hf-170, Ta-170), Lu-171 (Hf-171, Ta-171), Lu-172 (Hf-172,Ta-172), Lu-173 (Hf-173, Ta-173), Hf-172 (Ta-172, W-172, Re-172), Hf-173 (Ta-173, W-173),Hf-175 (Ta-175, Re-175, Os-175), Re-181 (Os-181, Ir-181), Re-182 (Os-182, Ir-182, Pt-182),Re-183 (Os-183, Ir-183, Pt-183, Au-183), Os-182 (Ir-182, Pt-182, Au-182, Hg-182), Os-185(Ir-185, Pt-185, Au-185, Hg-185), Os-191 (Re-191), Ir-185 (Pt-185, Au-185, Hg-185), Ir-186(Pt-186, Au-186, Hg-186), Ir-187 (Pt-187, Au-187, Hg-187), Ir-188 (Pt-188, Au-188, Hg-188),Ir-189 (Pt-189, Au-189, Hg-189), Ir-190, Ir-192, Pt-188 (Au-188, Hg-188), Pt-191 (Au-191,Hg-191), Au-193 (Hg-193), Au-194 (Hg-194), Au-195 (Hg-195), Au-196, Hg-193, Hg-194,Hg-195, Hg-195m, Hg-197, Hg-197m

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International Codes and Model Intercomparison for Intermediate Energy Activation Yields

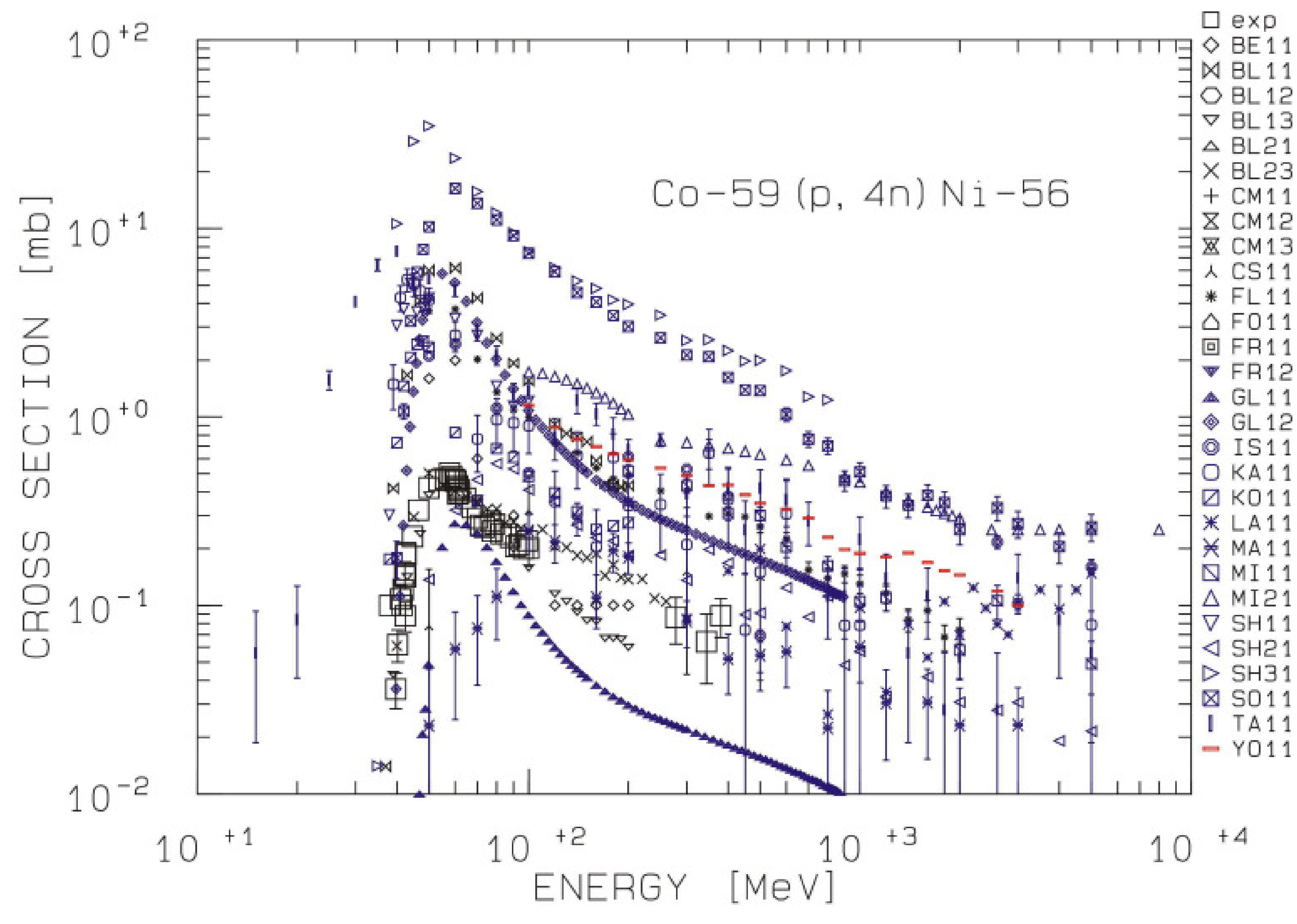
Blind intercomparison

E < 5 GeV

target elements: O, Al, Fe, Co, Zr, Au

code	physical model employed	code used	options used	energy range in MeV
BE11	PE + EVAP via MASTER EQ.	PEQAG2 (extended)		50 - 200 (Fe, Co) 26 - 200 (Zr,Au)
BL11	PE + EVAP	ALICE 92	Fermi gas level densities	7 - 200
BL12	PE + EVAP	ALICE 92	Chadwick level densities	1 - 200
BL13	PE + EVAP	ALICE 92	Kataria-Ramamurty level densities	1 - 200
BL21	HMS + EVAP	HMS-ALICE	Fermi gas level densities	3 - 290
BL23	HMS + EVAP	HMS-ALICE	Kataria-Ramamurty level densities	12 - 250
CM11	FKK + EXCITON + HAUSER FESHBACH EVAP	FKK-GNASH	no evaporation of Be-7	10 - 200
CM12	FKK + EXCITON + HAUSER FESHBACH EVAP	FKK-GNASH	no evap. of H-3, He-3 and Be-7	8 - 200
CM13	FKK + EXCITON + HAUSER FESHBACH EVAP	FKK-GNASH		15 - 200
CS11	QMD + SDM	QMDRELP+SDMRELP		50 - 5000
FL11	INC + EVAP	HET/BRUYERE		50 - 200
FO11	INC + MSM	PACE + MSM		100 - 300 (Al), 800 (Fe, Co), 900 (Zr), 1000 (Au)
FR11	INC + EVAP	ISABEL-EVA	local thomas fermi density approximation for momenta	100 - 1000
FR12	INC + EVAP	ISABEL-EVA	uniform thomas fermi density approximation for momenta	100 - 1000
GL11	PE + EVAP (GDH)	AREL	Myers-Swiatecki (MS) masses	10 - 900
GL12	PE + EVAP (GDH)	AREL	exp. + MS masses + shell corr.	10 - 900
IS11	INC + PE + EVAP + FRAGMENTATION	HETC-FRG		10 - 5000
KA11	INC + EVAP	INUCL		4 - 5000
KO11	FKK + EVAP	MINGUS		8 - 200
LA11	INC + SMM + EVAP	ISABEL/SMM		200 - 5000
MA11	INC + PE + EVAP	CEM 95		10 - 5000
MI11	INC + EVAP	HET-KFA2		200 - 5000
MI21	TSAO & SILBERBERG SYSTEMATICS	SPALL (modified)/YIELD		10 - 5000
SH11	PE + EVAP	ALICE -IPPE		3 - 100
SH21	INC + EVAP	CASCADE		50 - 5000
SH31	INC + EVAP	DISCA		14 - 800
SO11	INC + PE + SMM + EVAP + FERMI BREAKUP	MSDM		1 - 5000
TA11	INC + PE + EVAP	HETC-3STEP		15 - 5000
YO11	INC + EVAP	MECC7 + EVAP_F		100 - 3000

R. Michel, P. Nagel, NSC/DOC(97)-1, NEA, 1997



R. Michel, P. Nagel, NSC/DOC(97)-1, NEA, 1997

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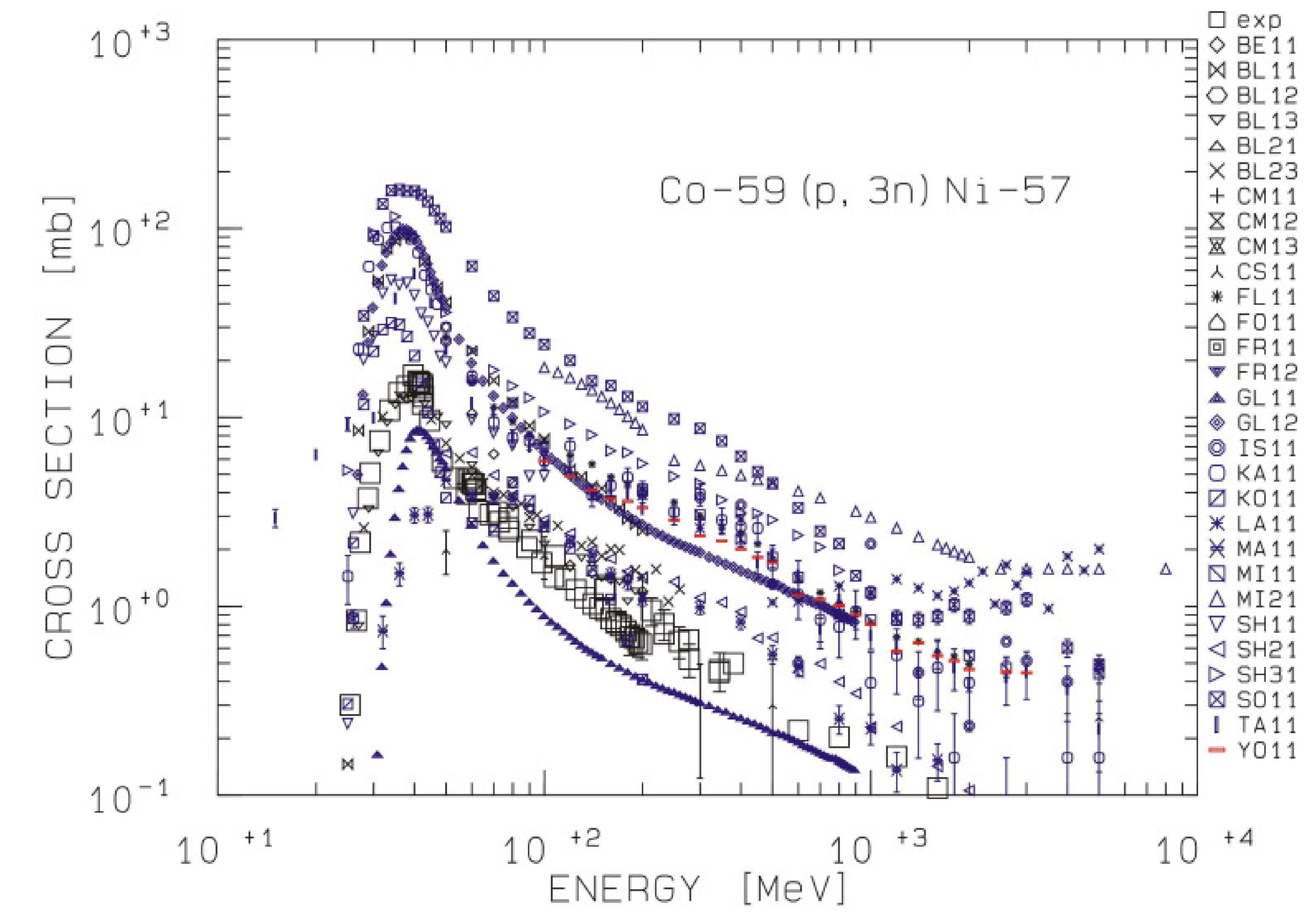

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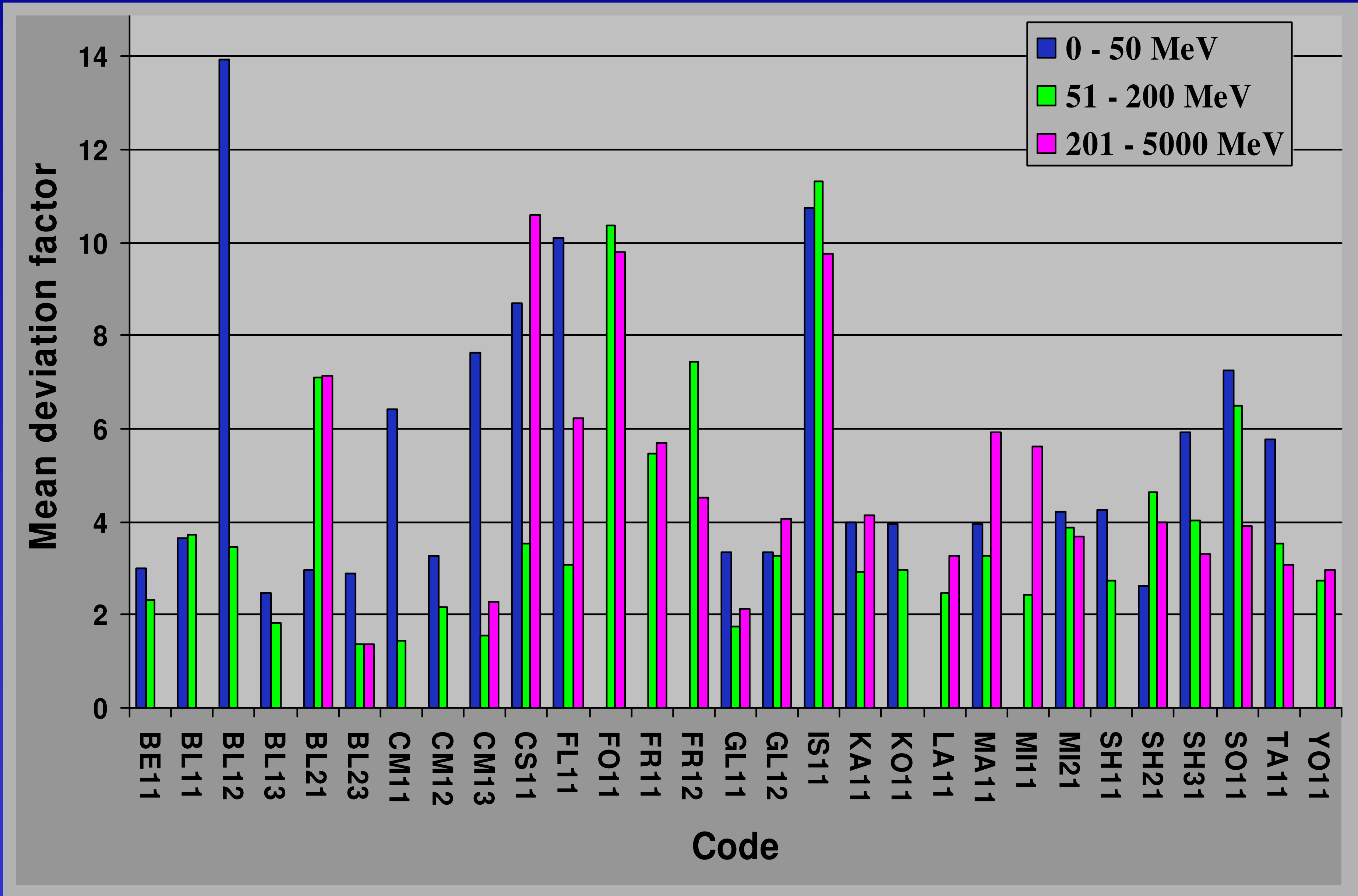

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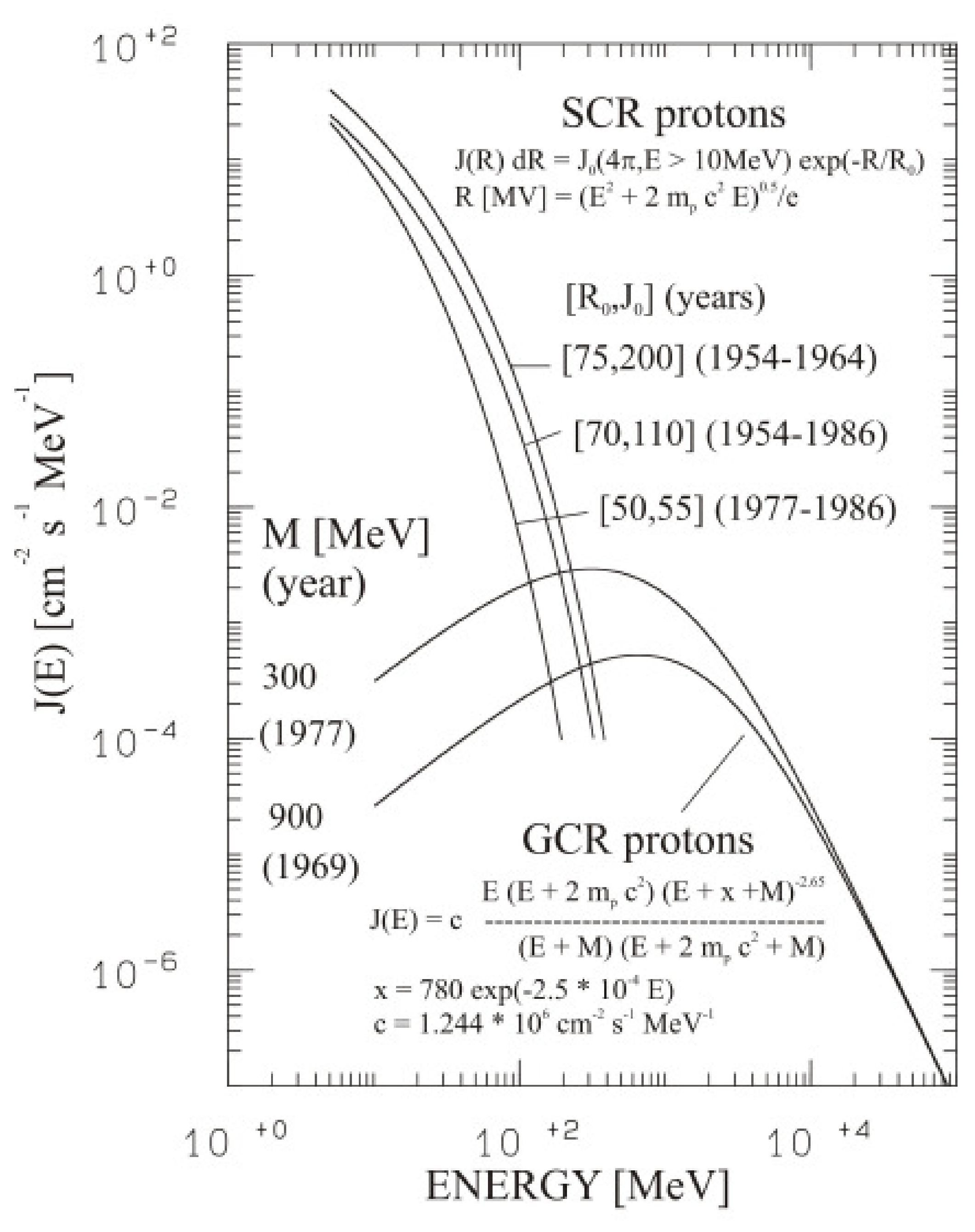
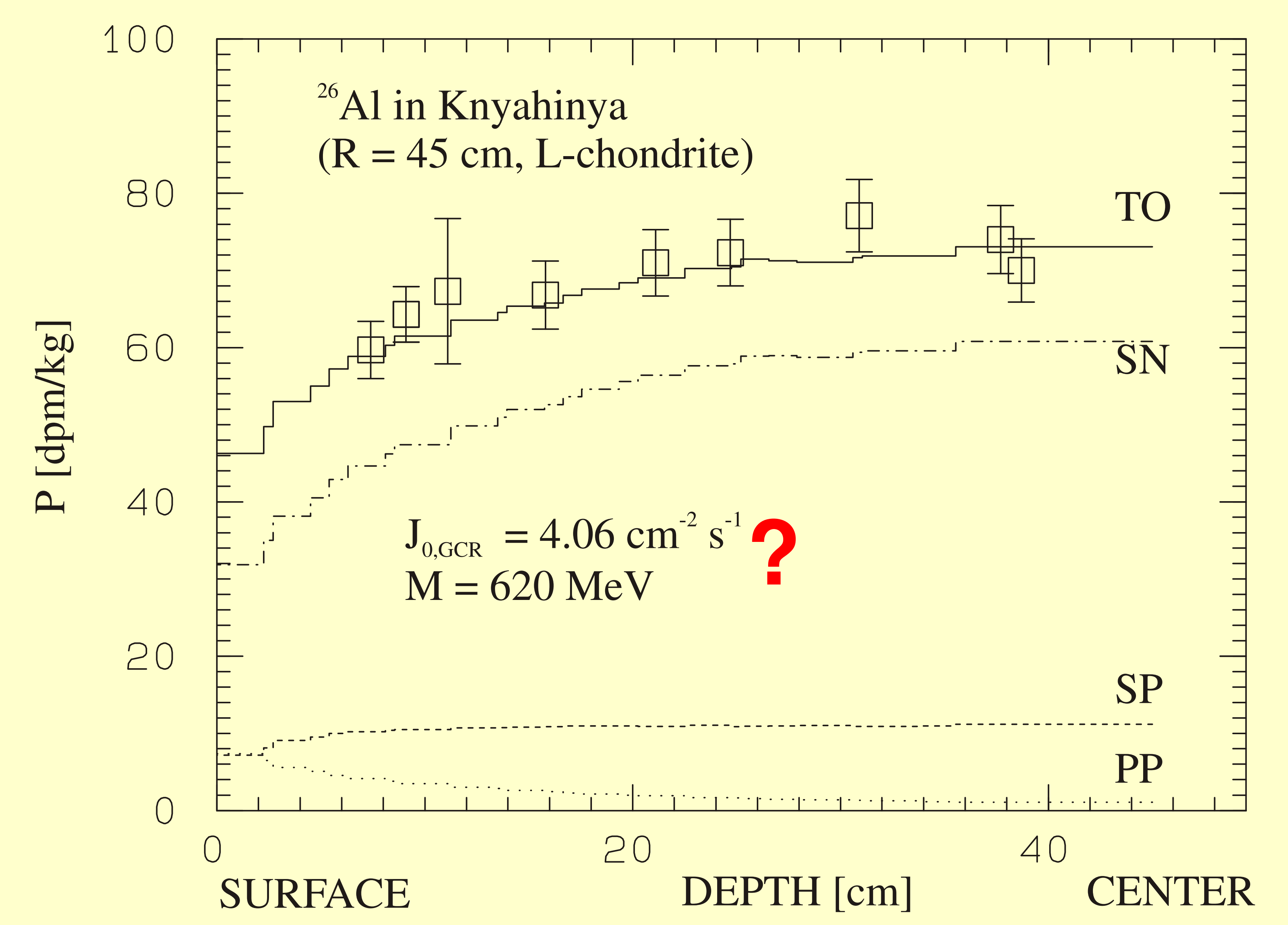


Mean SCR-spectra for three solar 11-years cycles and extremes of GCR-spectra observed.

Michel et al. (1996)

Stony Meteorite Knyahinya

- Chondrite (L5)
- fell on 9. Juni 1866
  in Ukraine
- recovered mass ca. 300 kg



^{26}Al in Knyahinya
(R = 45 cm, L-chondrite)
$J_{0,GCR} = 4.06\ cm^{-2}\ s^{-1}$
M = 620 MeV
?
TO
SN
SP
PP
P [dpm/kg]
100
80
60
40
20
0
0
20
40
SURFACE
DEPTH [cm]
CENTER

Simulation of the production of cosmogenic nuclides by isotropic irradiation of an artificial stony meteoroid with 1.6 GeV protons.

- R = 25 cm
- 1400 individual targets
- 27 elements
- in 282 h: simulation of 1,6 Ma in space

Simulation of the production of cosmogenic nuclides at LNS/Saclay by an isotropic irradiation of an artificial iron meteoroid with 1.6 GeV protons.

- R = 10 cm
- 870 individual targets
- 28 elements
- in 42 h: simulation of 3,0 Ma in space

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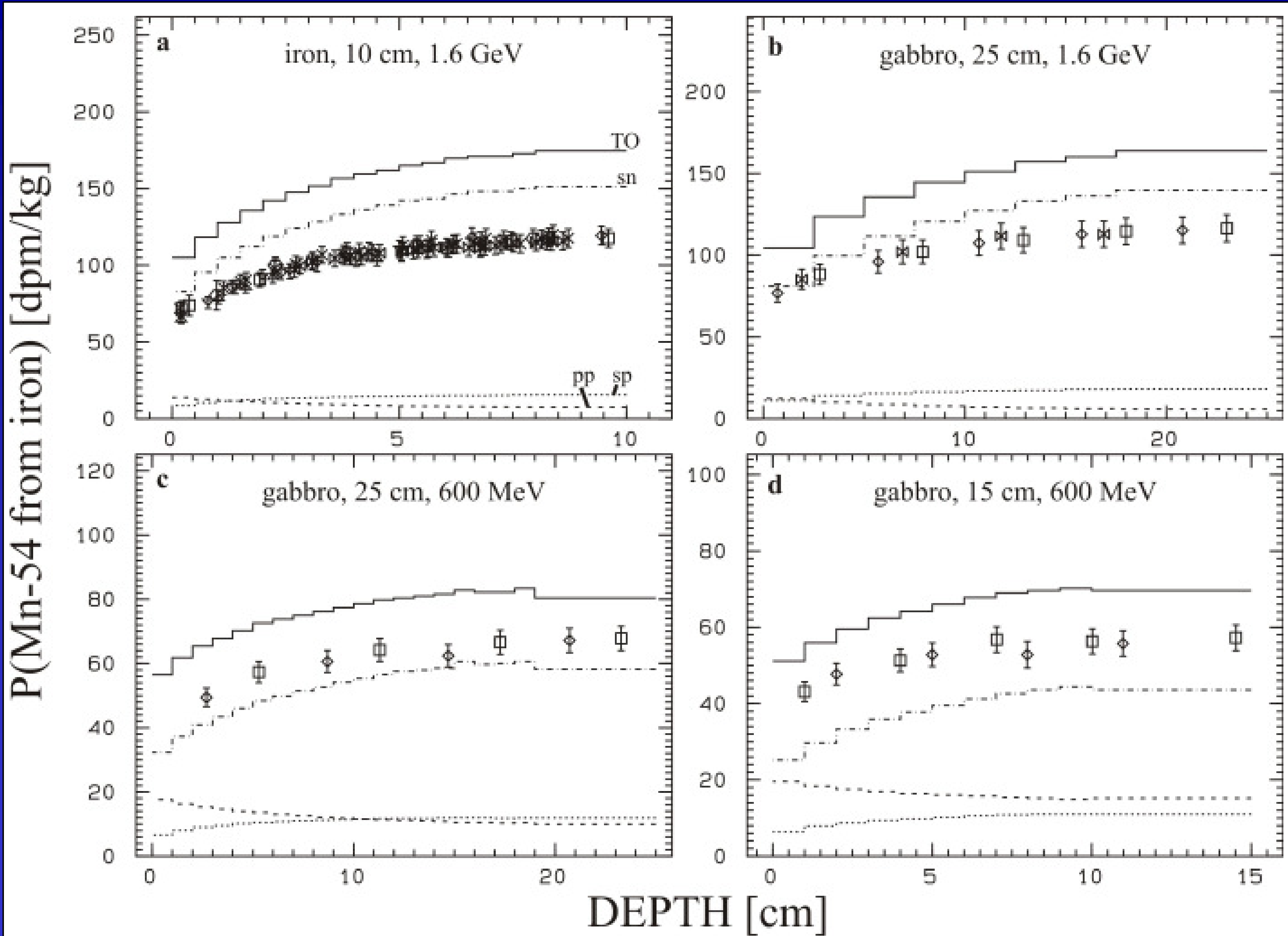

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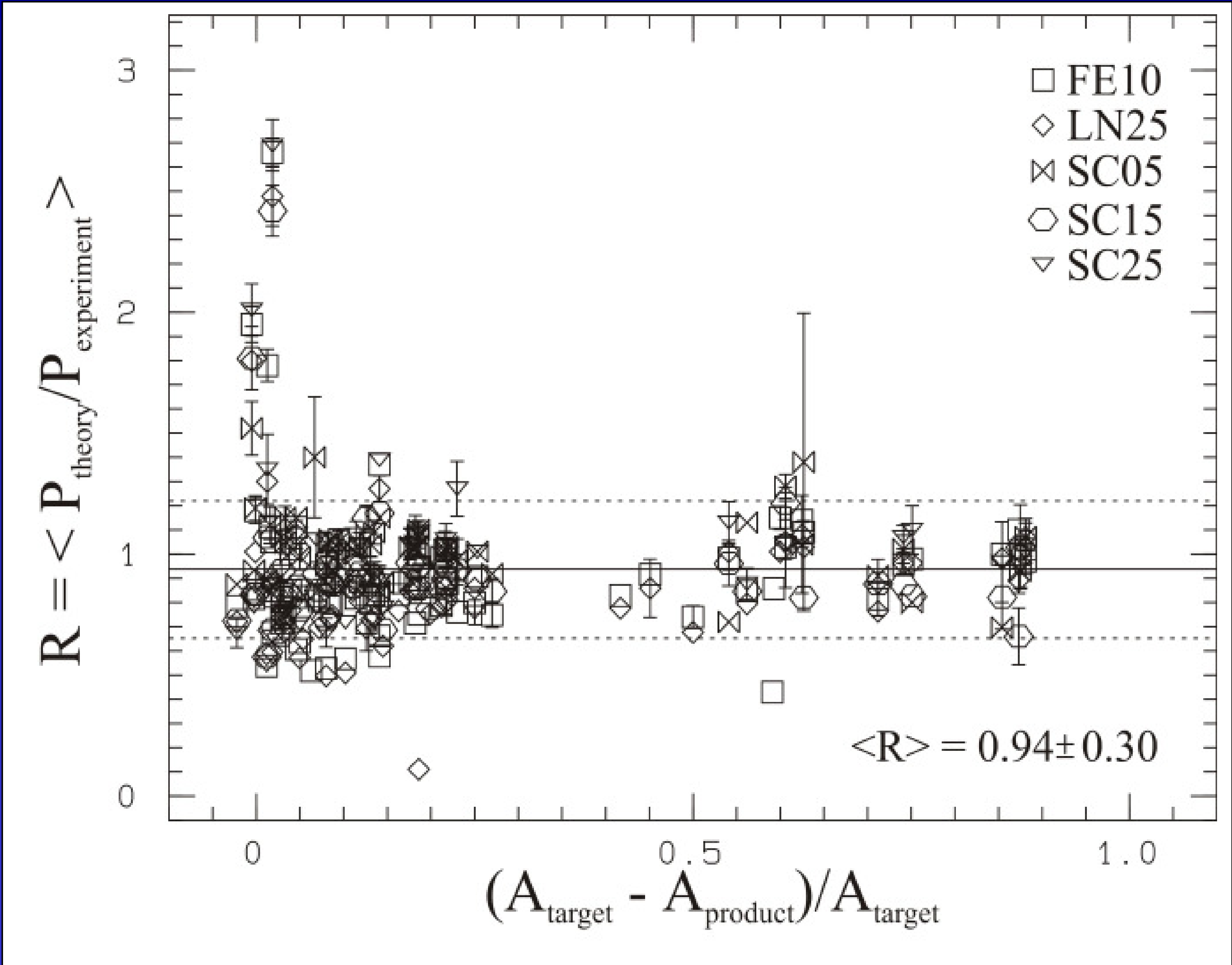

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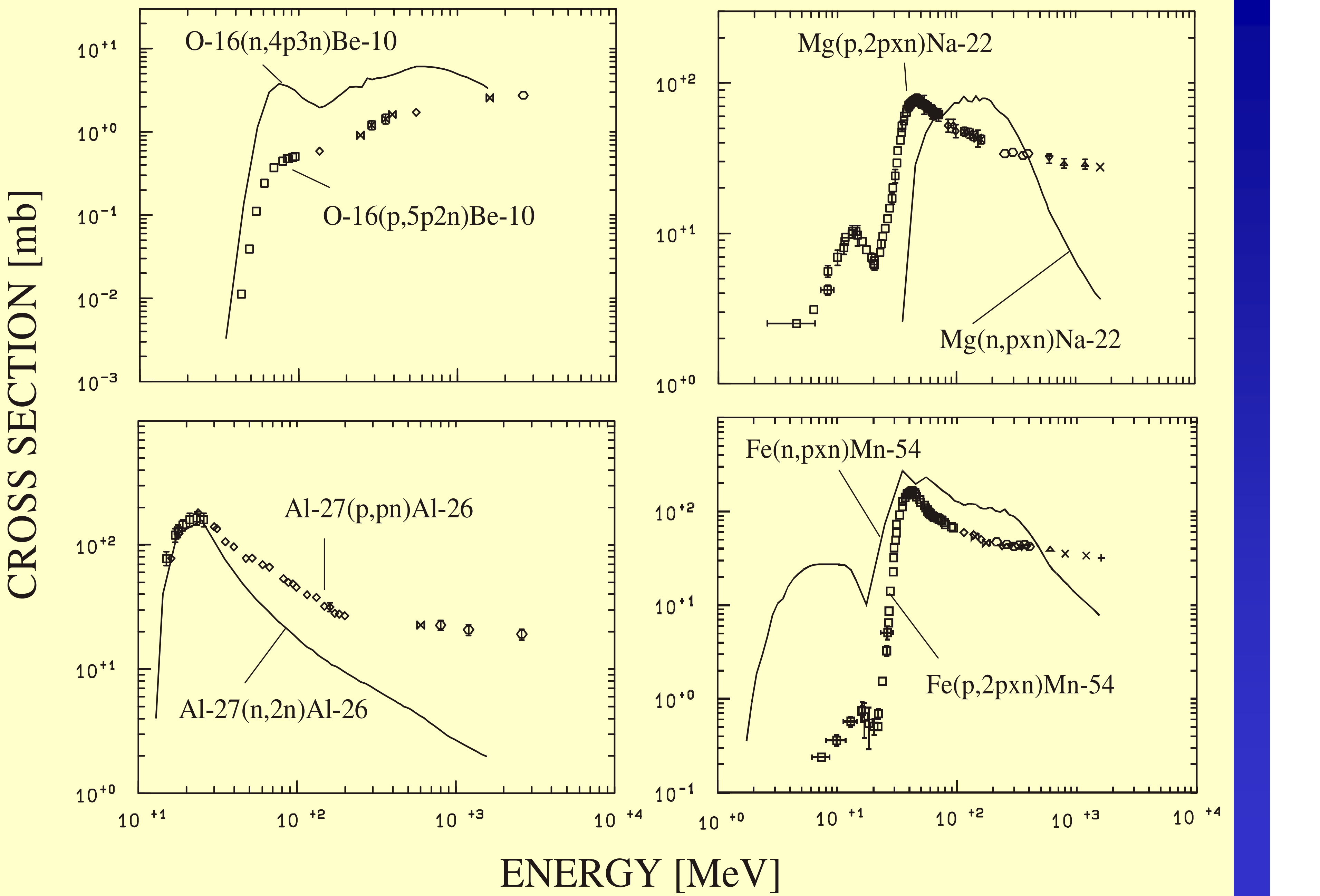
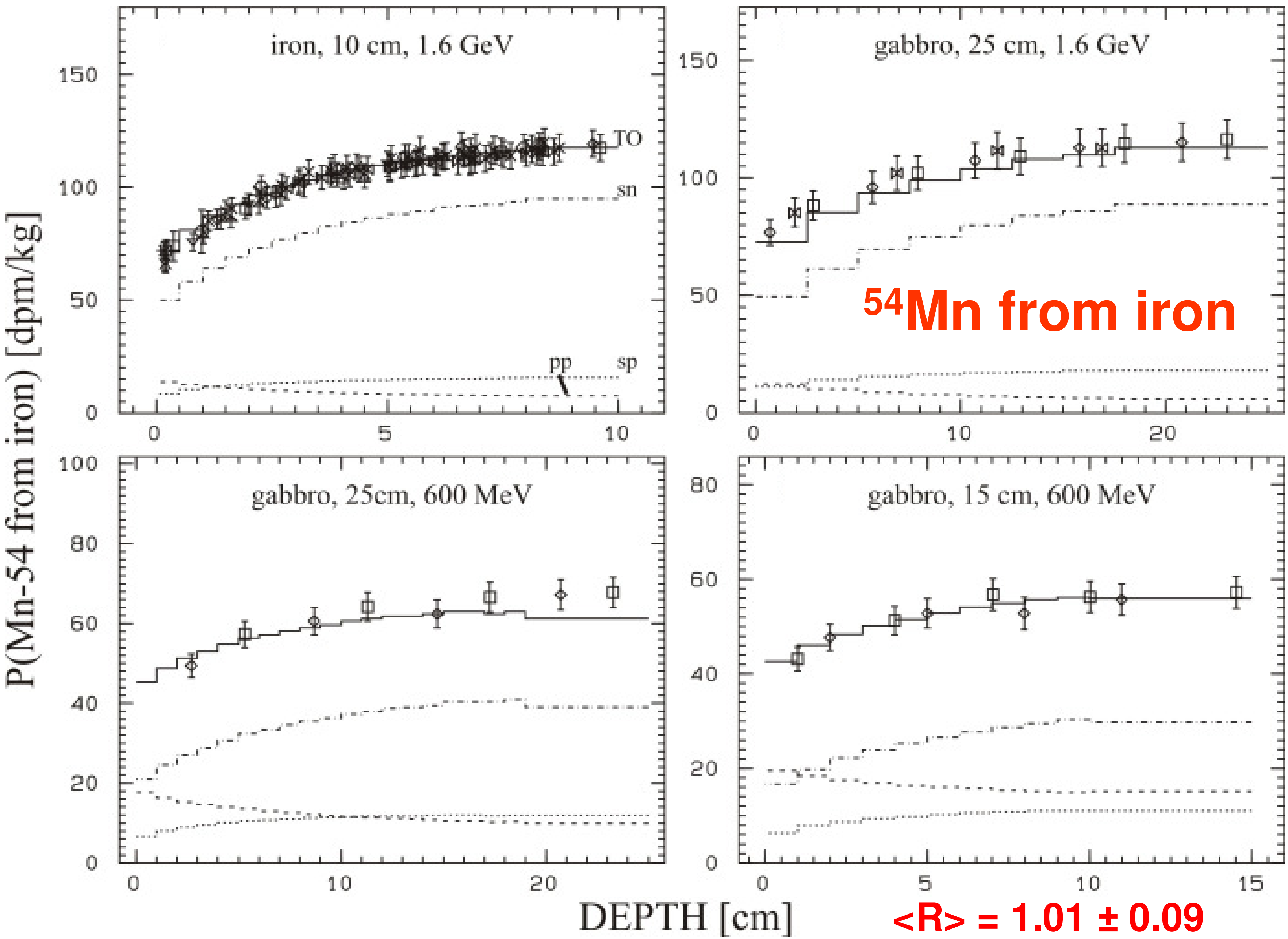
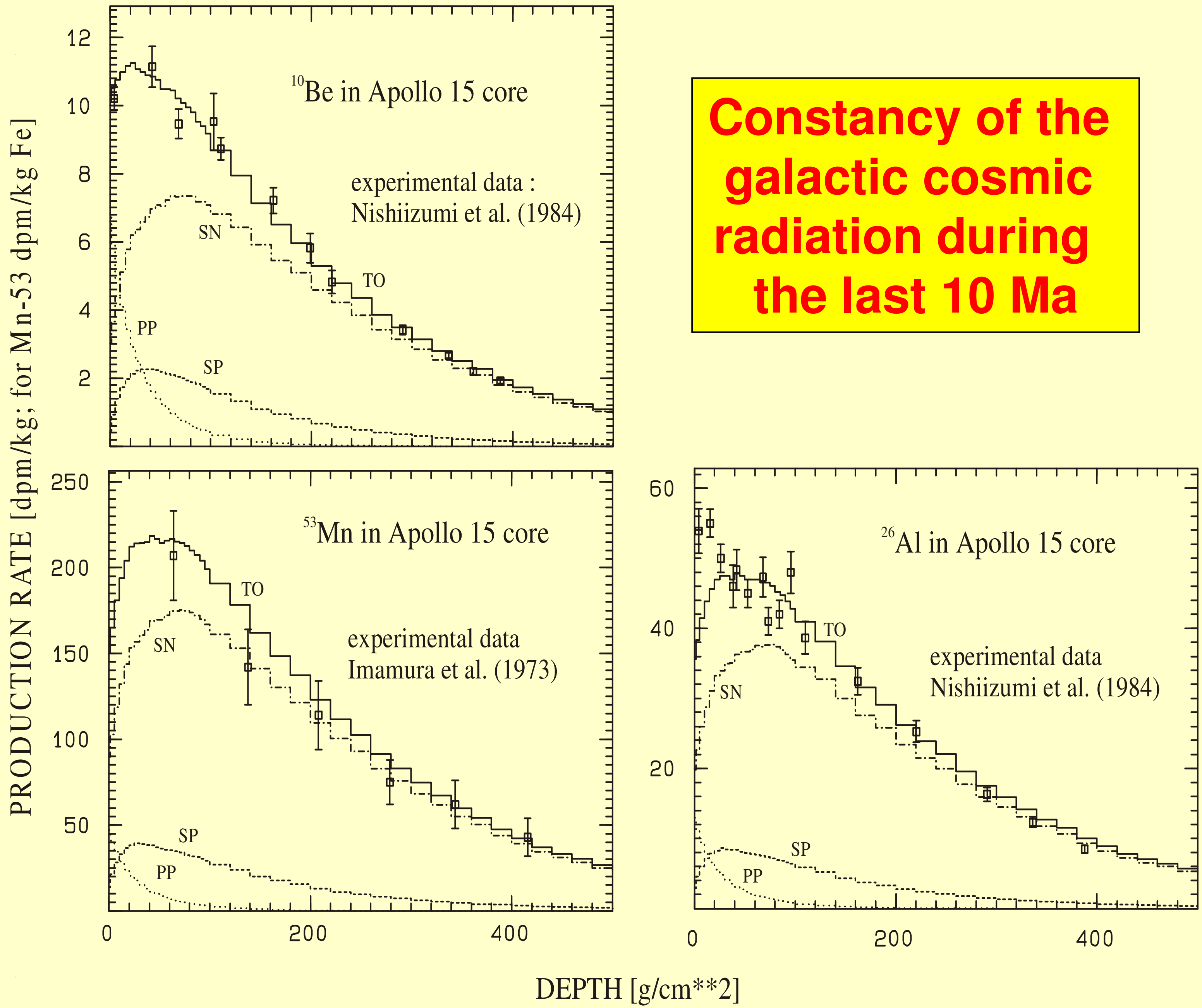


O-16(n,4p3n)Be-10
O-16(p,5p2n)Be-10
Mg(p,2pxn)Na-22
Mg(n,pxn)Na-22
Al-27(p,pn)Al-26
Al-27(n,2n)Al-26
Fe(n,pxn)Mn-54
Fe(p,2pxn)Mn-54
CROSS SECTION [mb]
ENERGY [MeV]



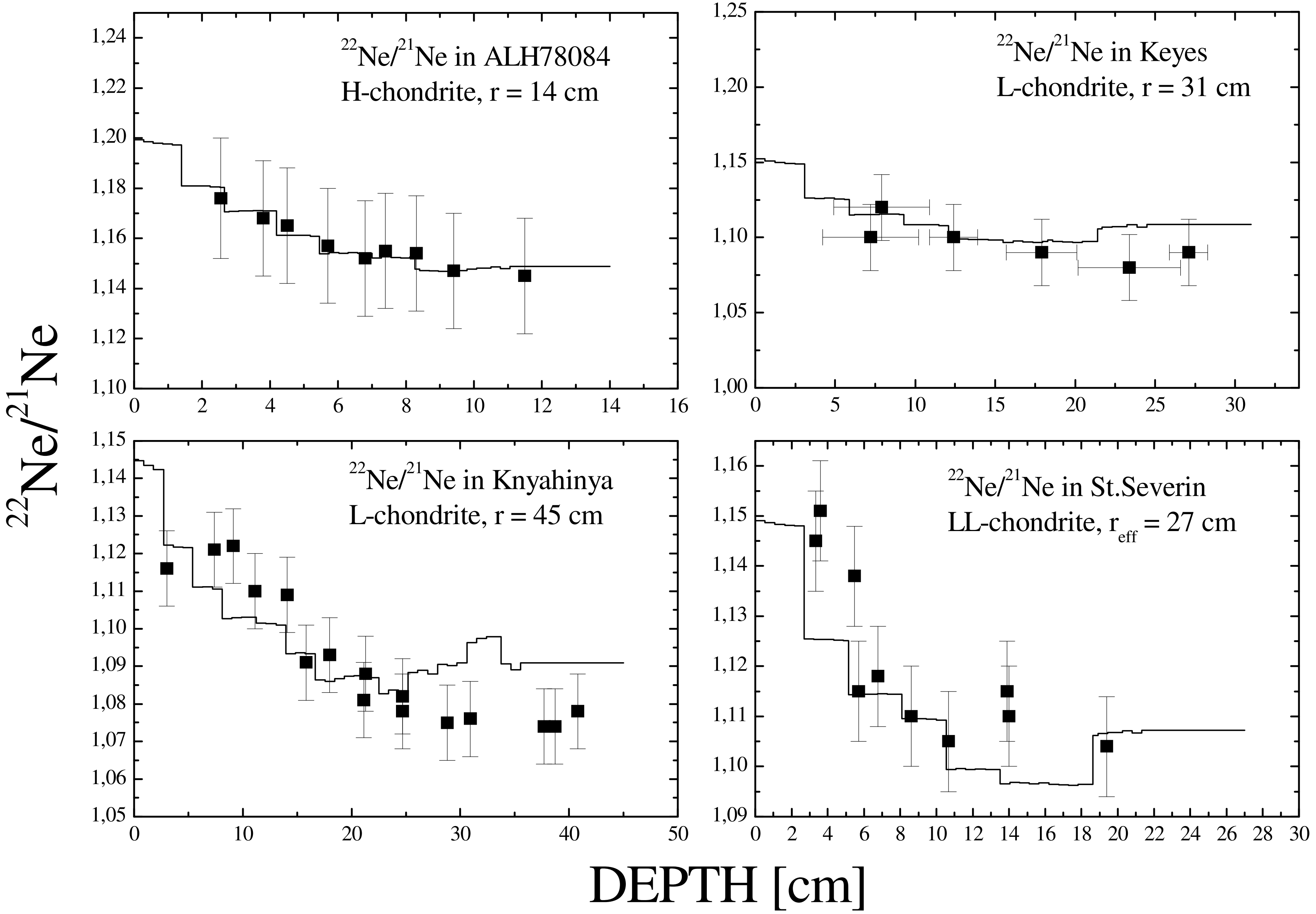
^{54}Mn from iron

<R> = 1.01 ± 0.09

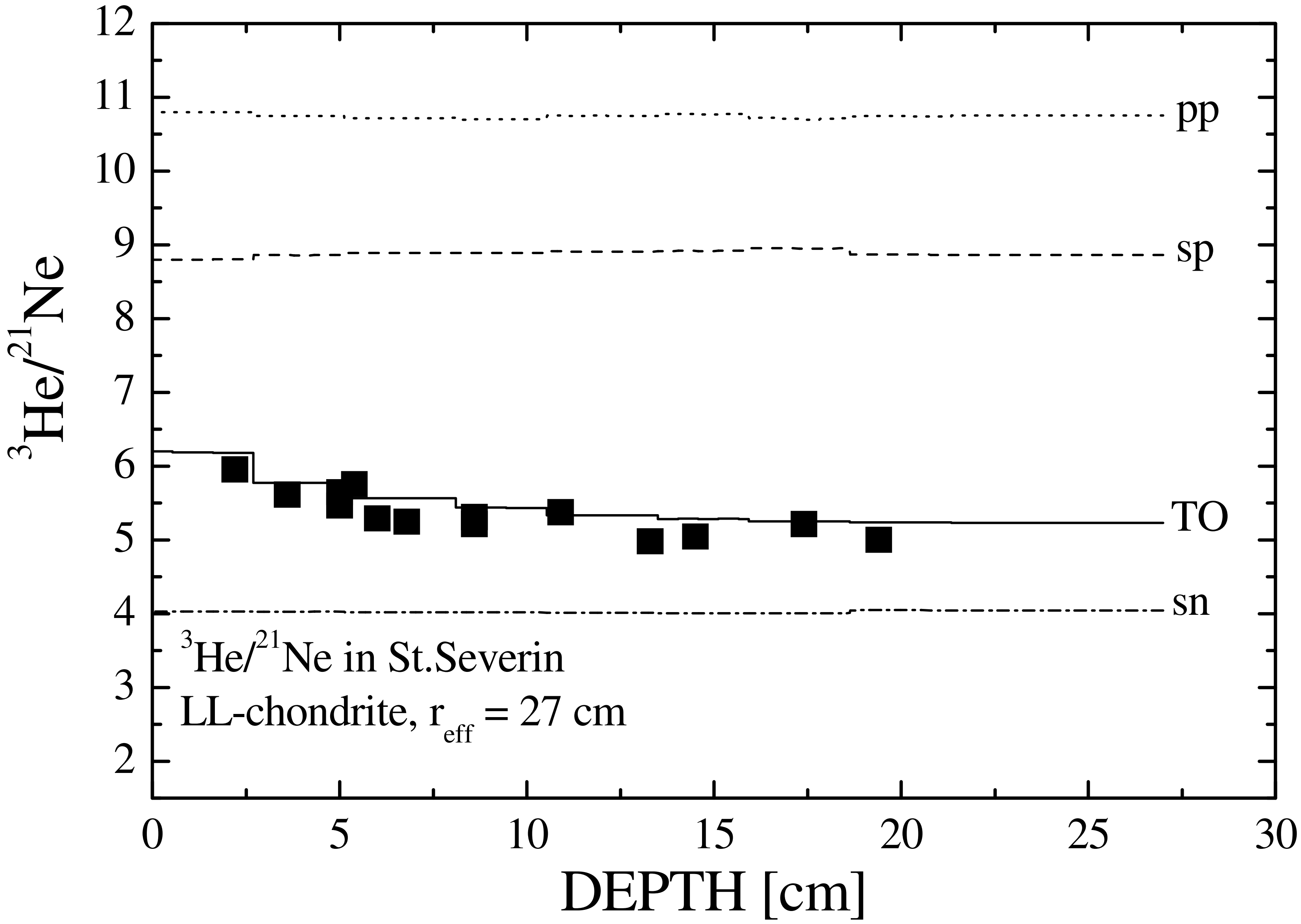


Constancy of the galactic cosmic radiation during the last 10 Ma

$^{22}Ne/^{21}Ne$ in chondrites



$^{3}He/^{21}Ne$ in St. Severin



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Data Needs of Accelerator-Driven Technologies

materials	target elements
air, water	N, O, Ar
concrete	C, O, Na, Mg, Al, Si, Ca, Mn, Fe
beam pipe	Mg, Al, Zn, Cu
stainless steel	Cr, Mn, Fe, Co, Ni
accelerator structural materials	Al, Cu, Fe, ...
spallation target	Na, Fe, Zr, Y, W, Ta, Hg, Pb, Bi, U, Th
fission products & actinides	Sr, Tc, I, Cs, Np, Pu, Am, Cm

It will not be possible to measure all data needed. One has largely to rely on calculated data.

High- and Intermediate Energy Nuclear Data for Accelerator-Driven Systems

HINDAS

Experimental and theoretical studies on the following elements:

1. One shielding material: Fe
2. One target element : Pb
3. One actinide: U

Task 1 : Experiments between 20 and 200 MeV

Task 2 : Experiments above 200 MeV

Task 3 : Theory (TALYS, INCL, ABLA) and evaluation

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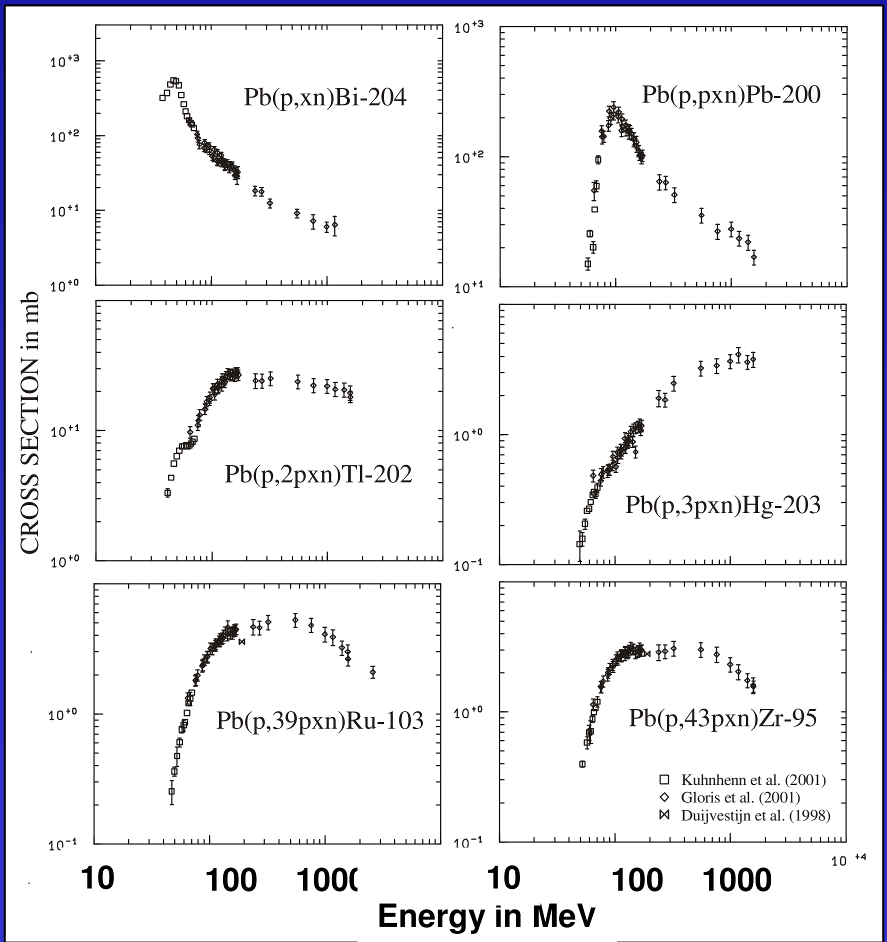
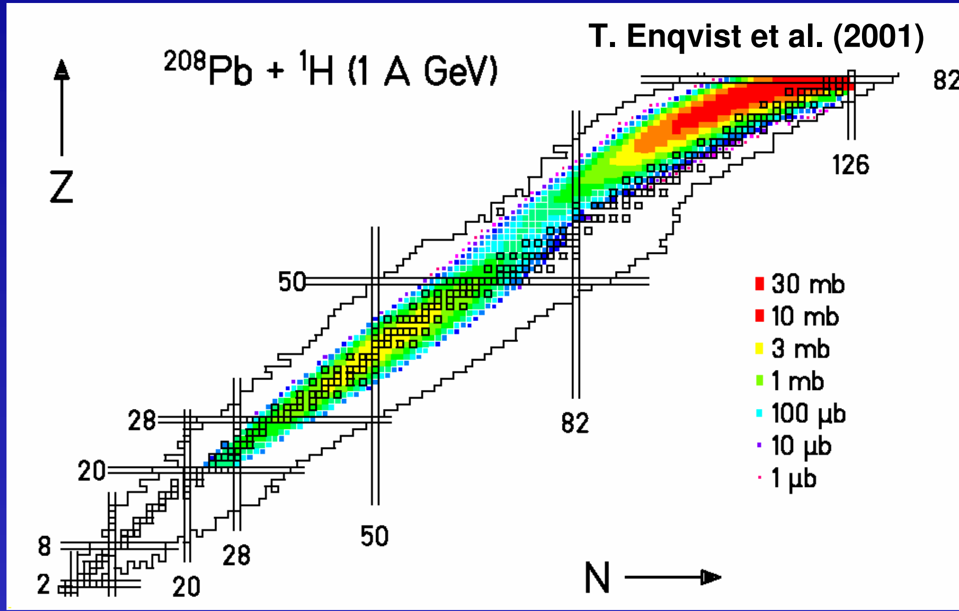
The two approaches: Classical versus Inverse Kinematics

Complete excitation functions for long-lived radionuclides and stable rare gas nuclides.





Complete product-nuclide spectrum at one energy (except very low masses).

Inventory of an accelerator-driven facility

- during operation
- shortly after shut-down

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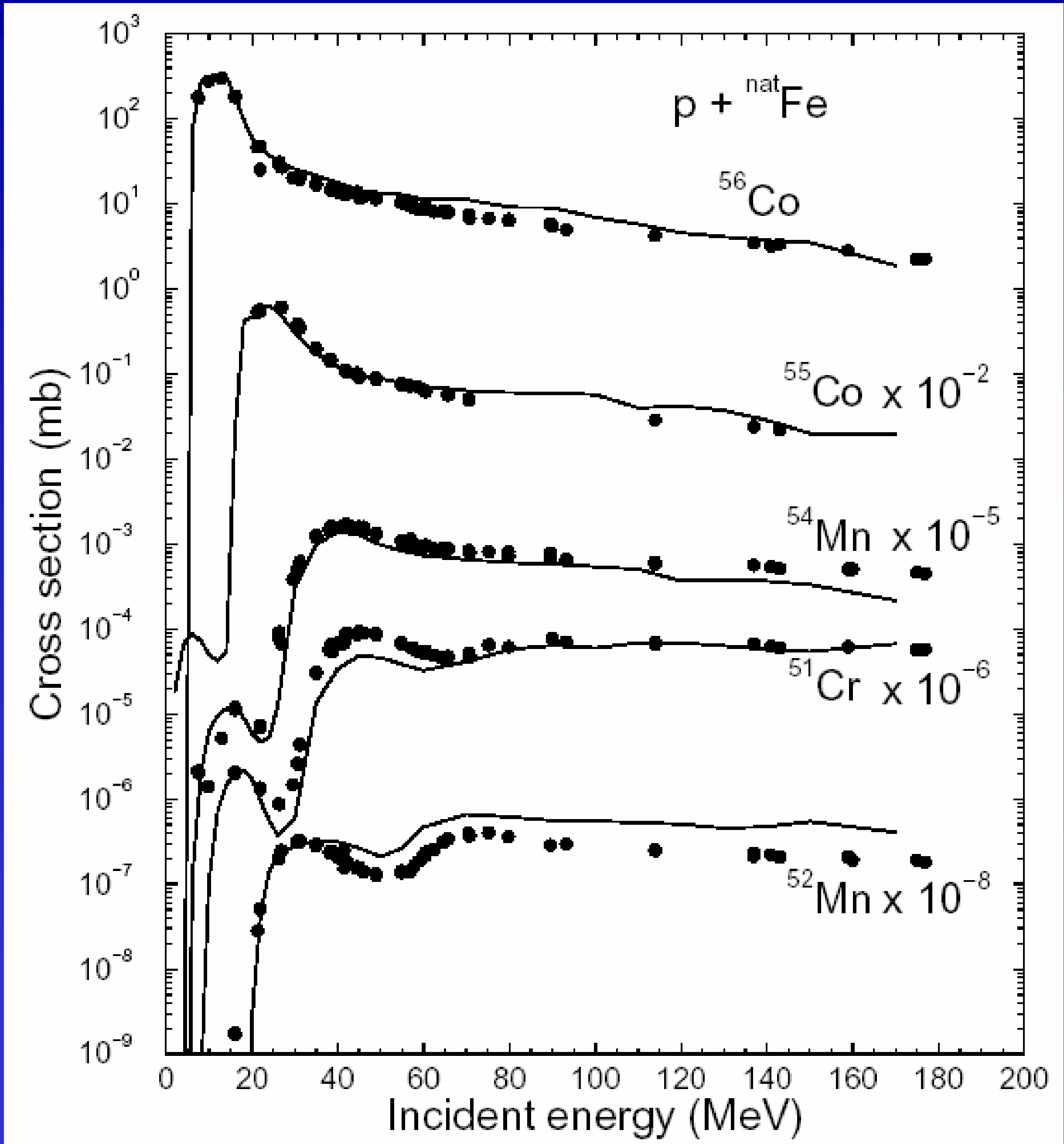
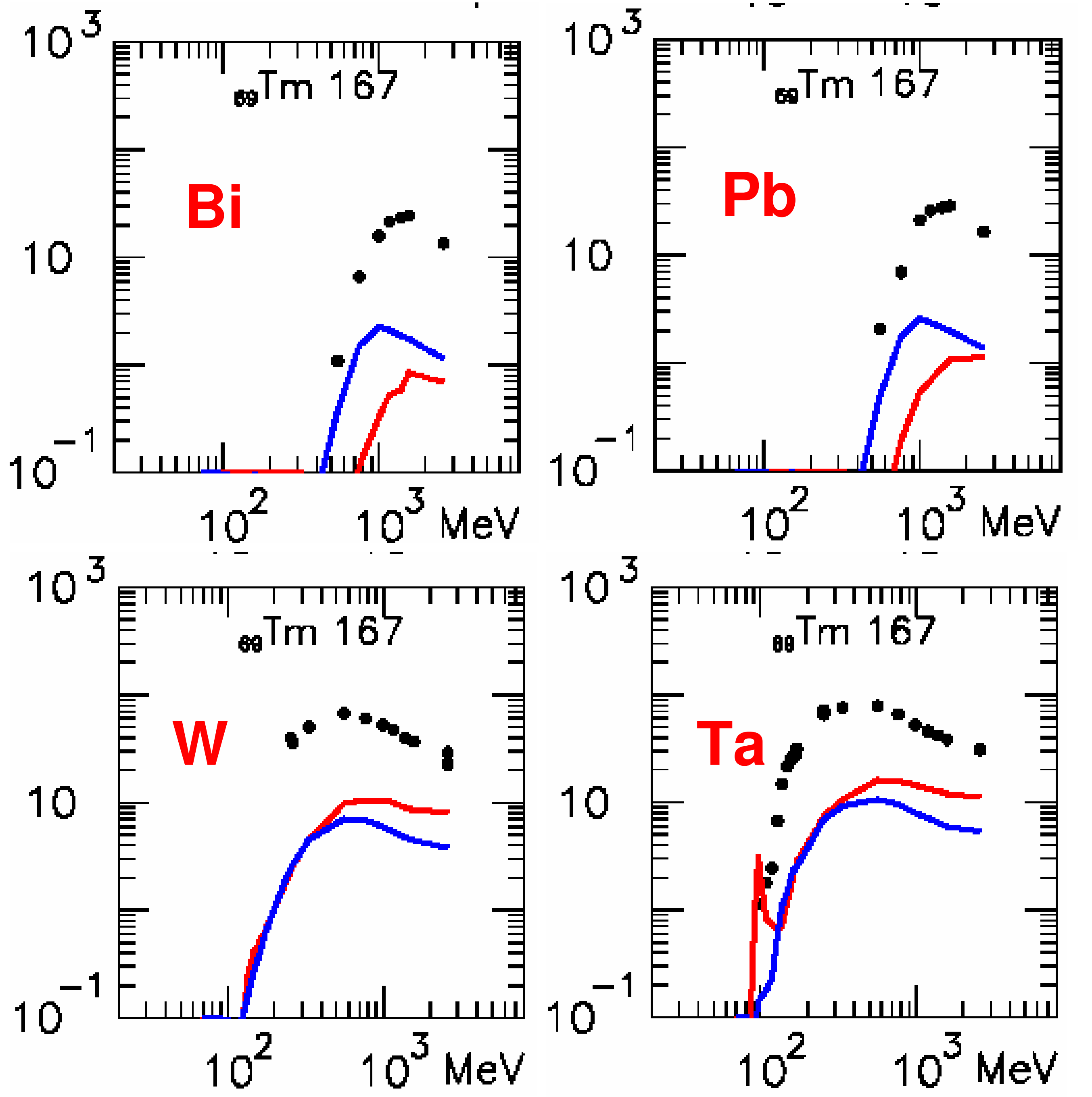


Modeling by the TALYS Code

A. Koning (2002)



Production of ^{167}Tm

Requirements for Testing the Performance of Model Codes

Comprehensive, systematic and representative coverage of

- **particle types,**
- **target elements,**
- **product nuclides,**
- **energies.**

Special reactions for testing extremes of nuclear reactions:

- **unbalanced nucleons in the exit channel,**
- **competition between spallation and fission,**
- **competition between evaporation, PE decay, and fission,**
- **(multi-)fragmentation.**

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Target Elements Investigated for the Production of Residual Nuclides by p-Induced Reactions

A consistent database containing
> 22 000 cross sections for more than
1000 target-product combinations.

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	110	111	112		114		116		118

lanthanides

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu

actinides

Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

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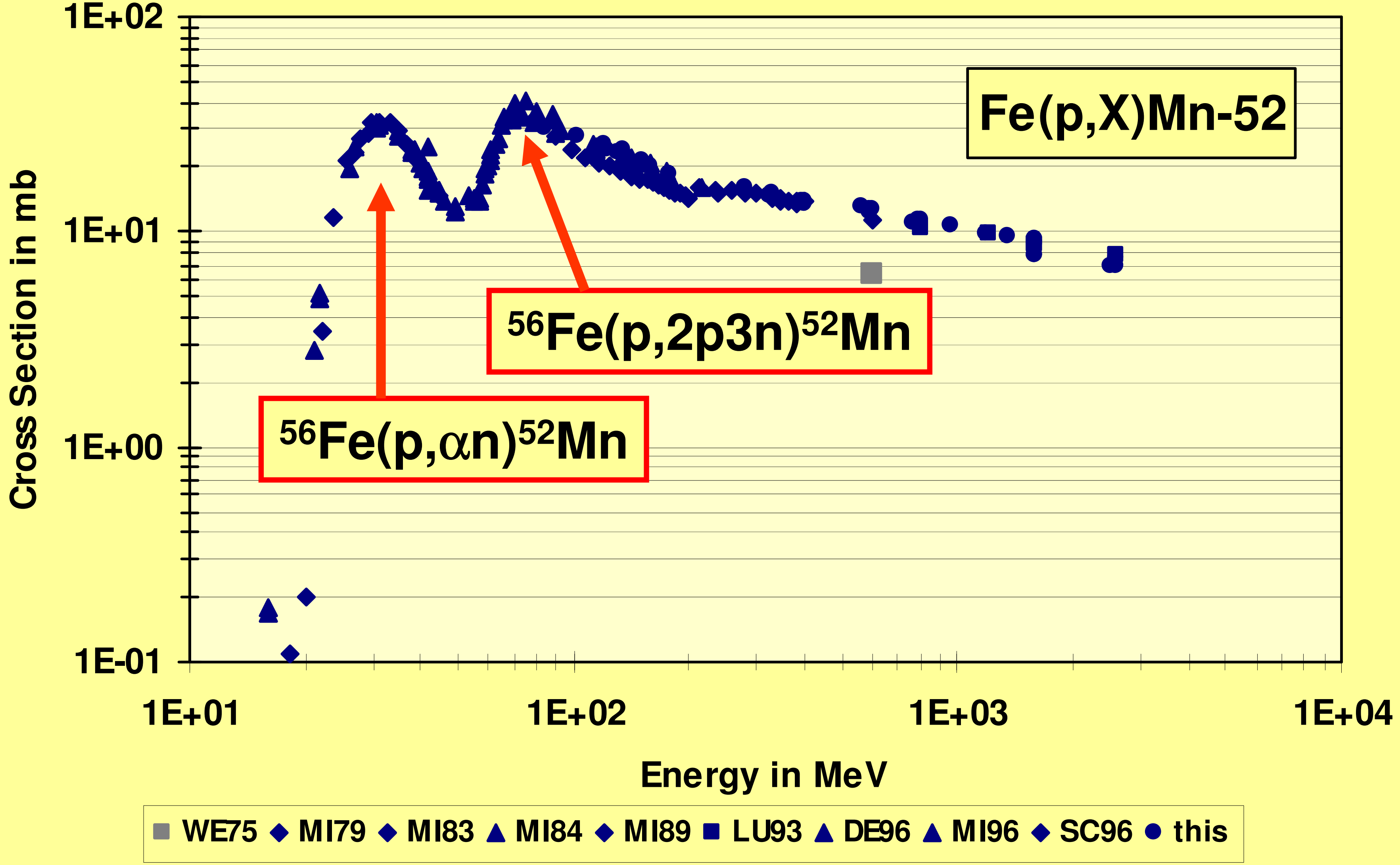

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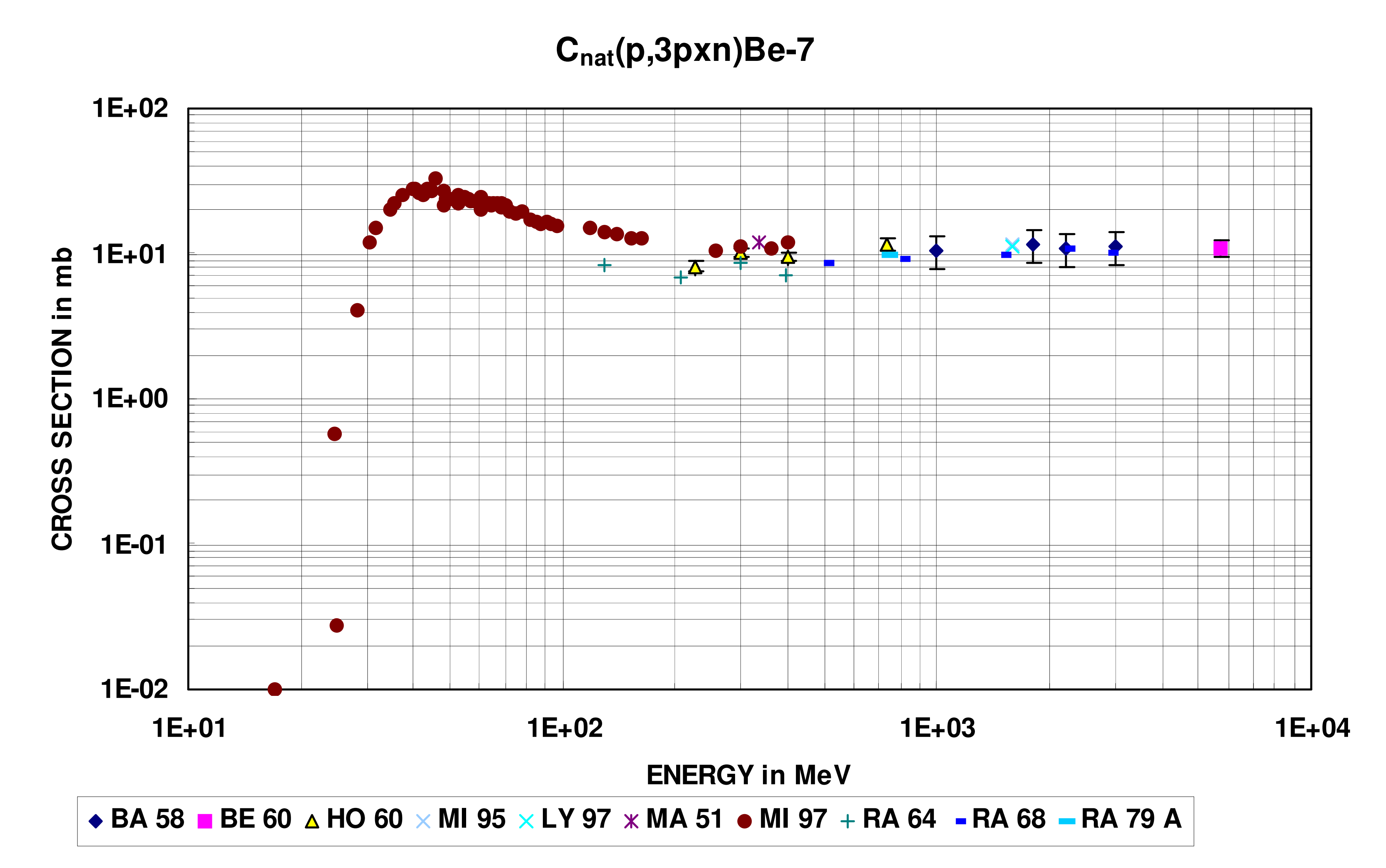

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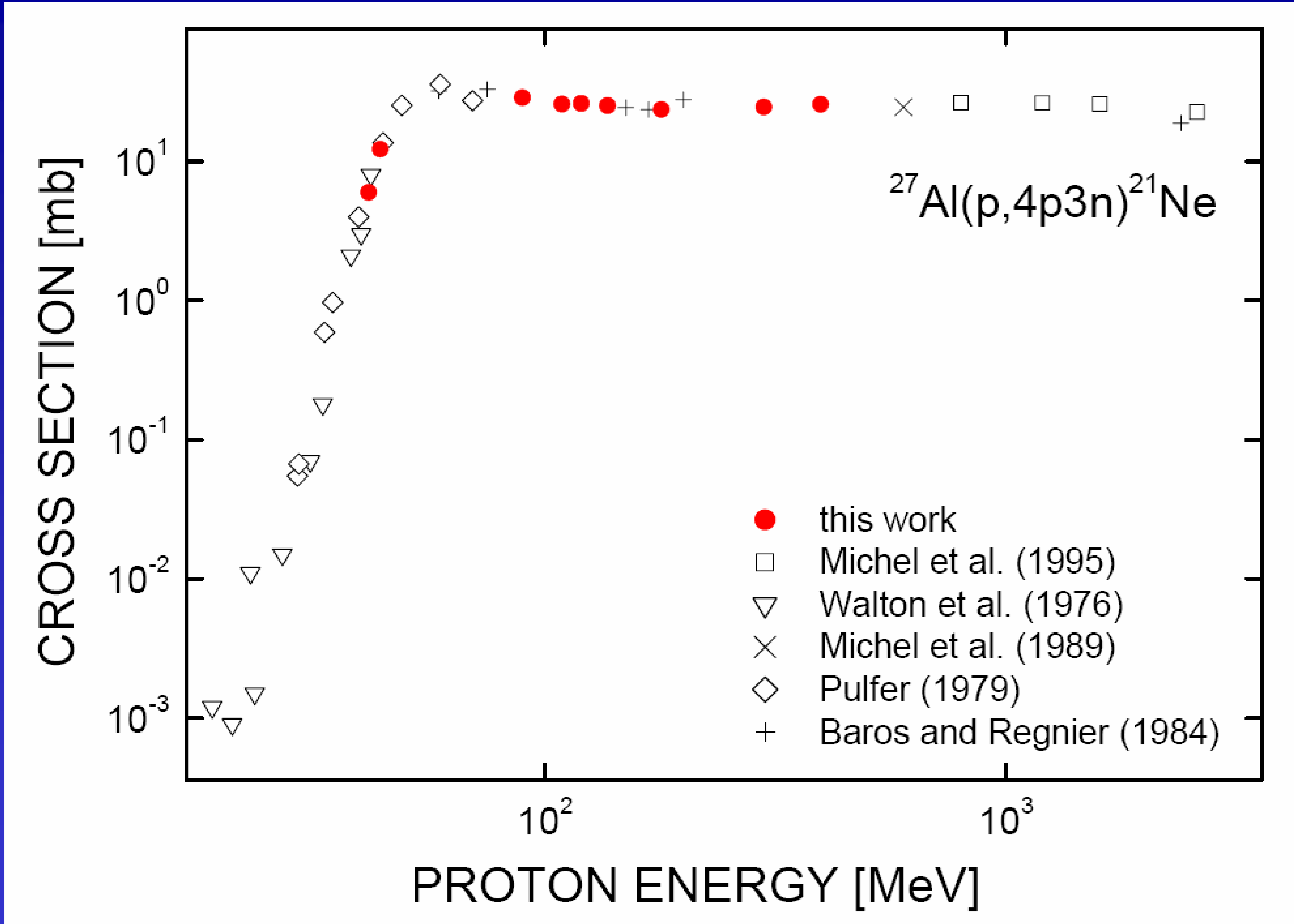
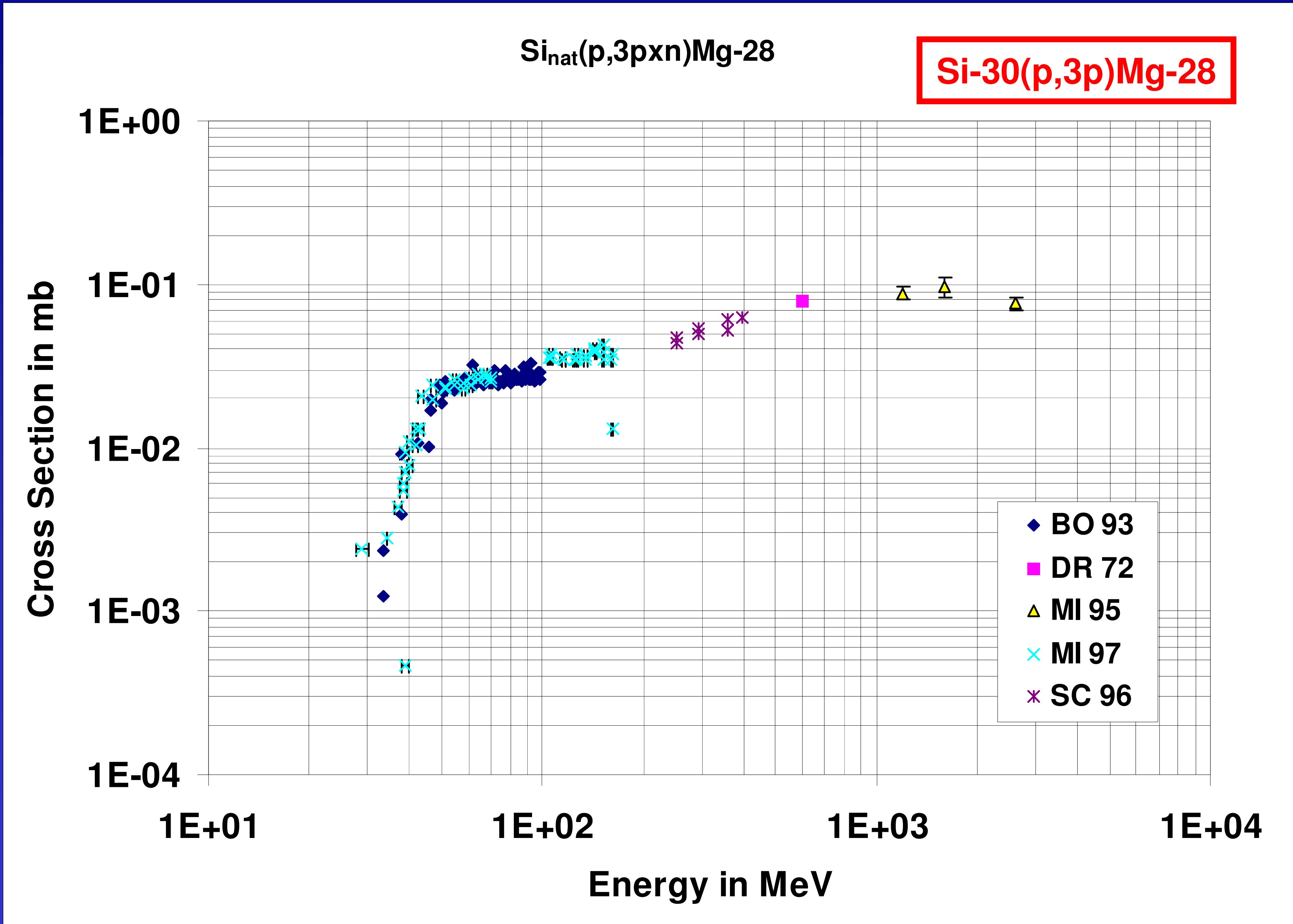
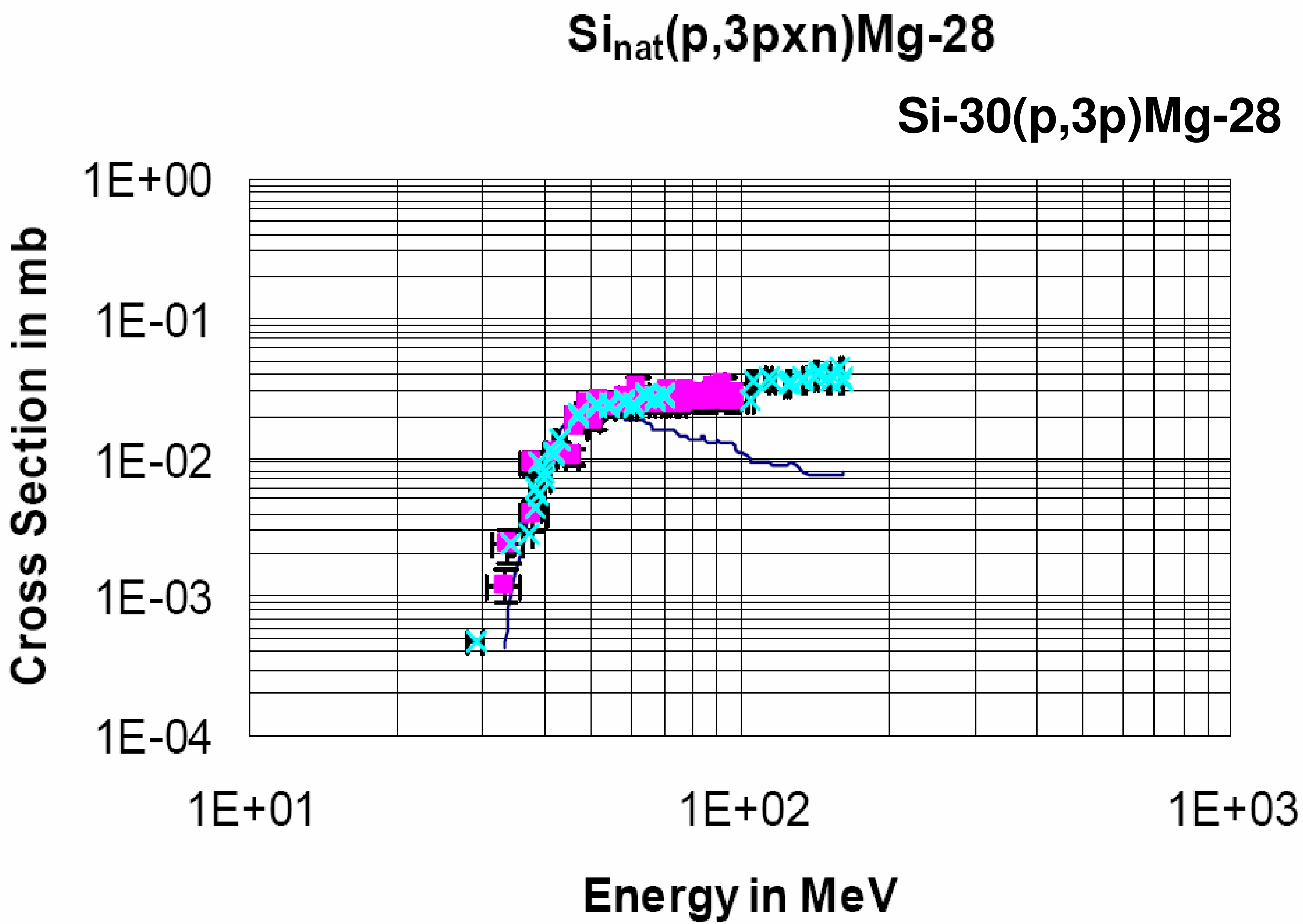


Leya et al. (2007)

Special reactions





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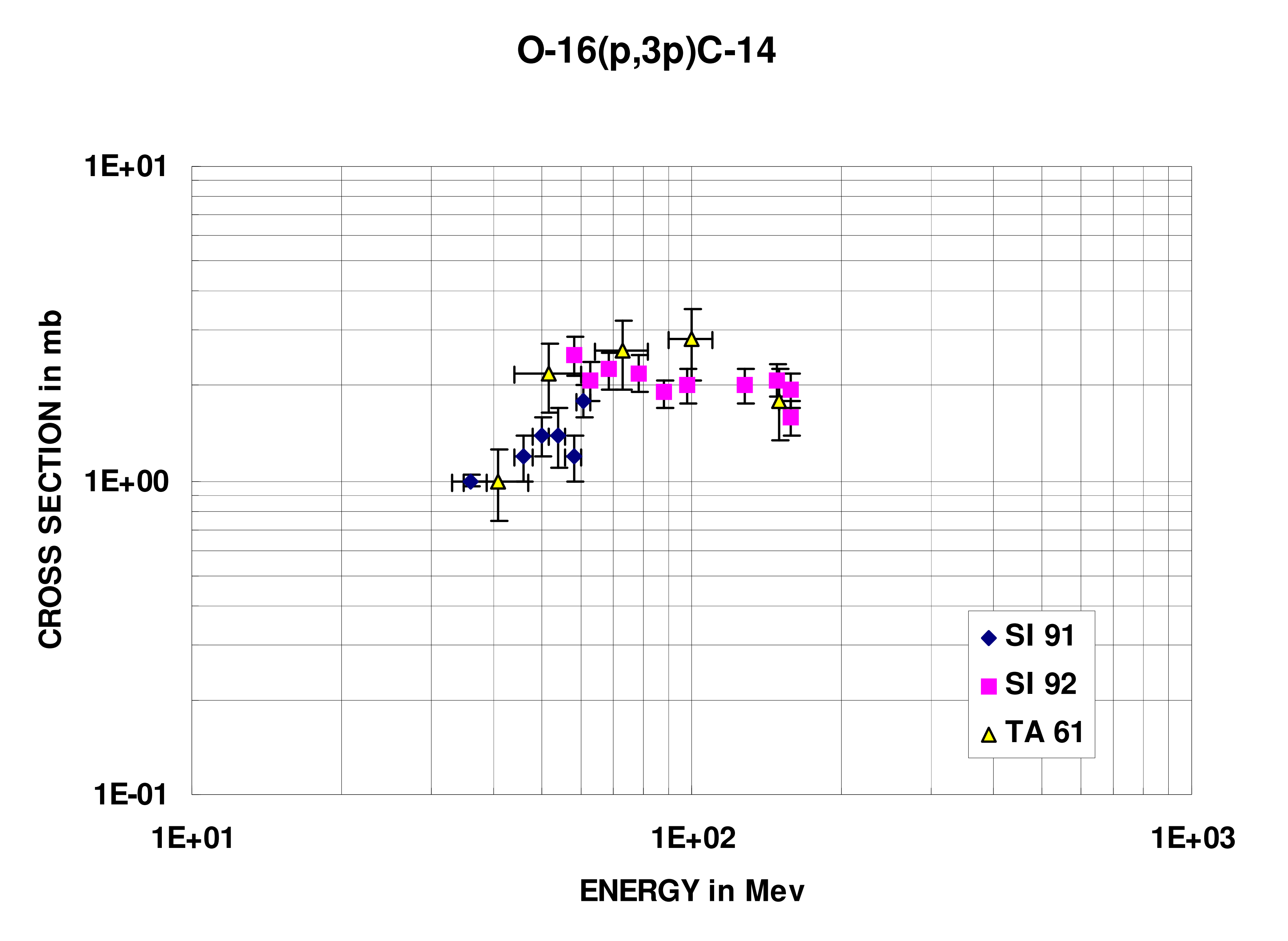
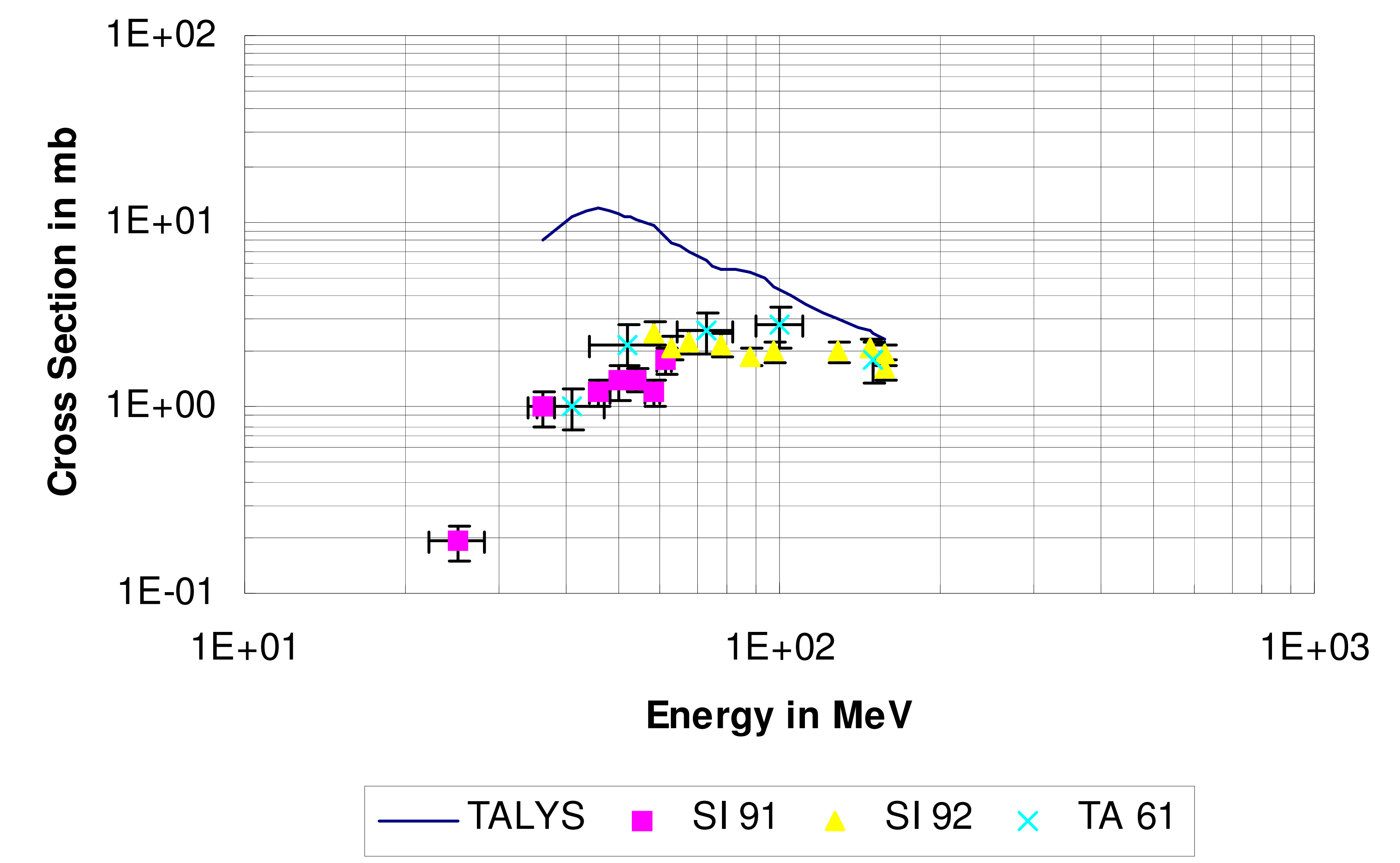
Special reactions



$^{16}O(p,3p)^{14}C$



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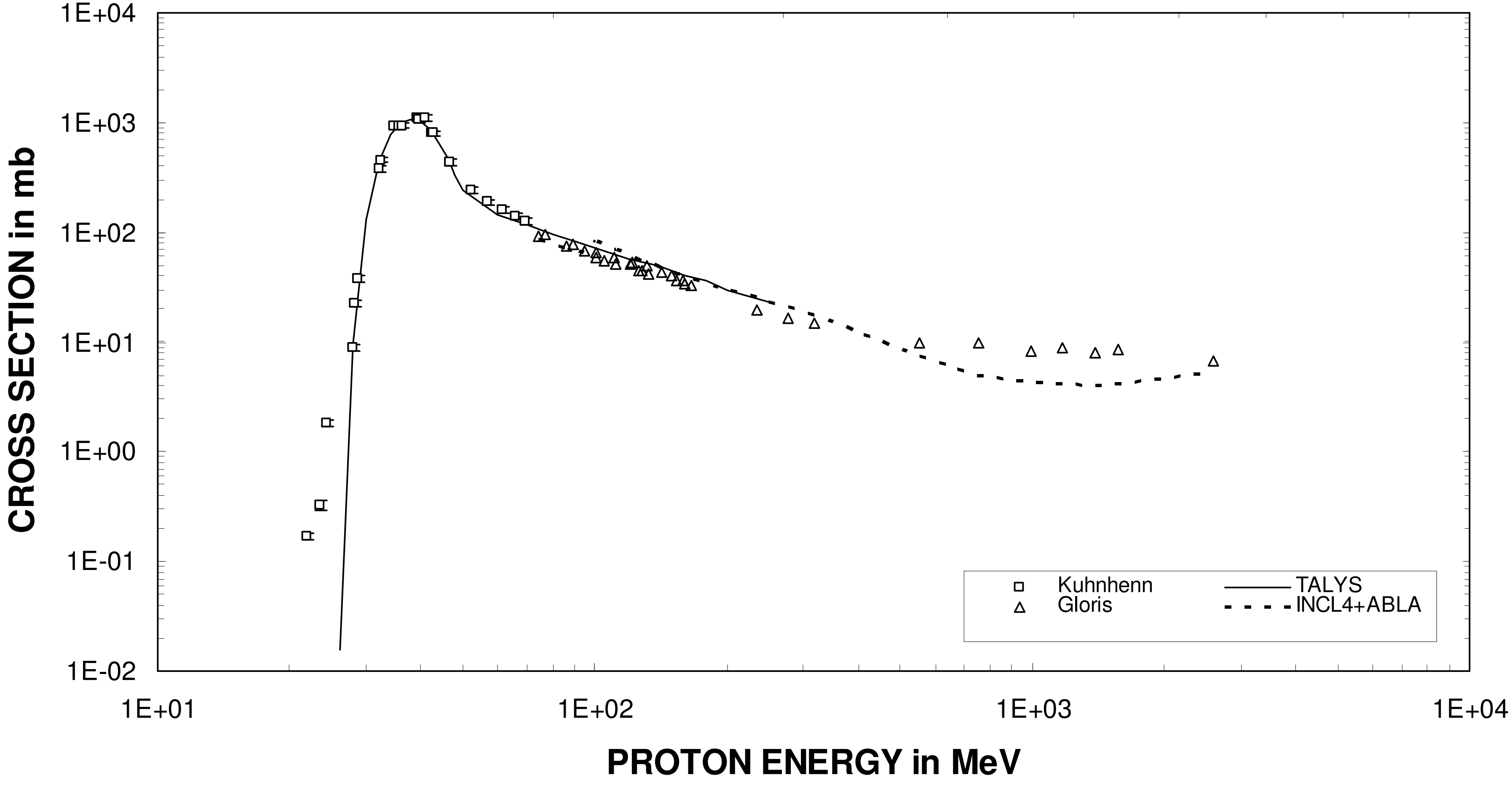
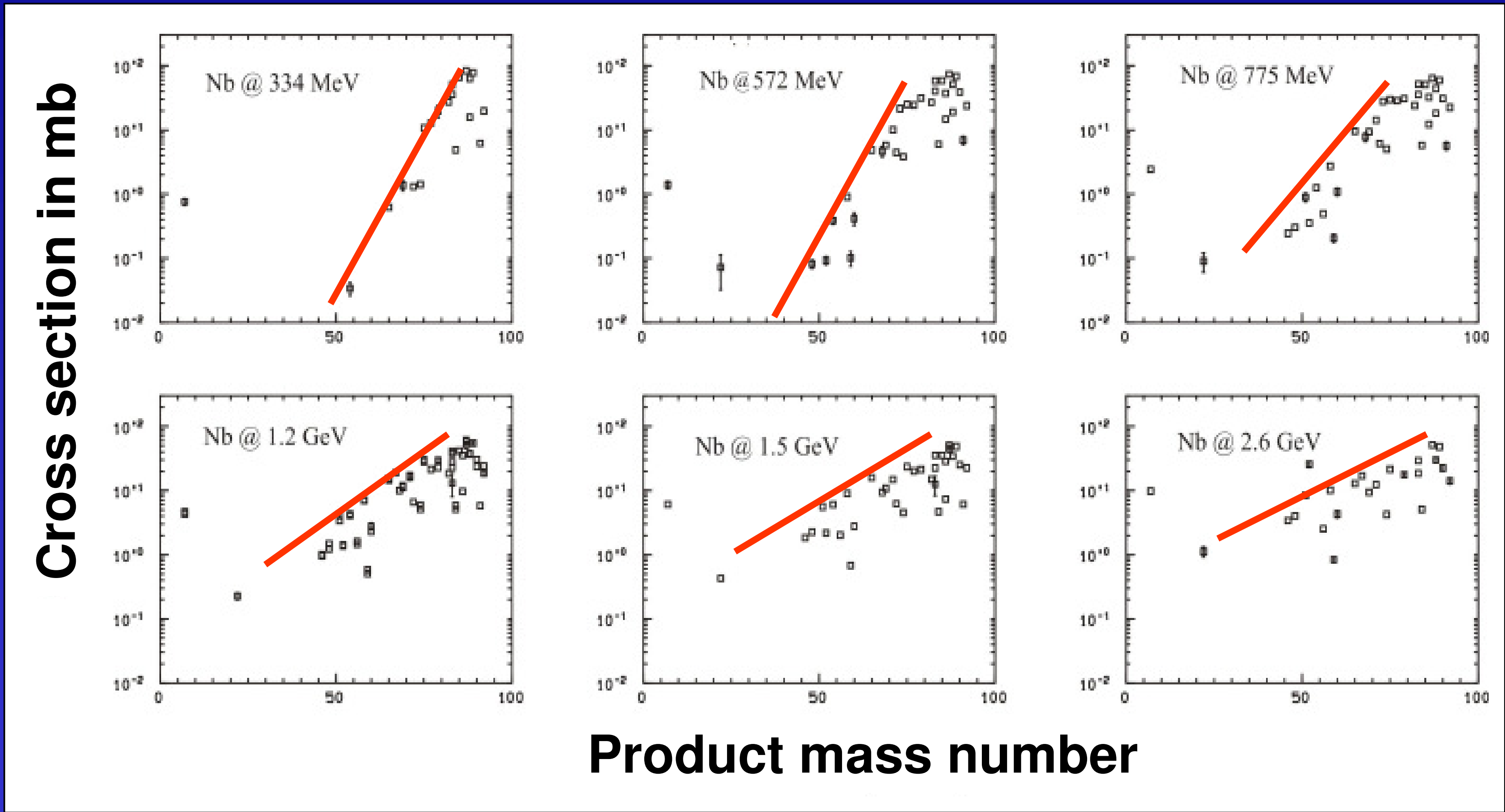
Bi(p,4n)Po-206

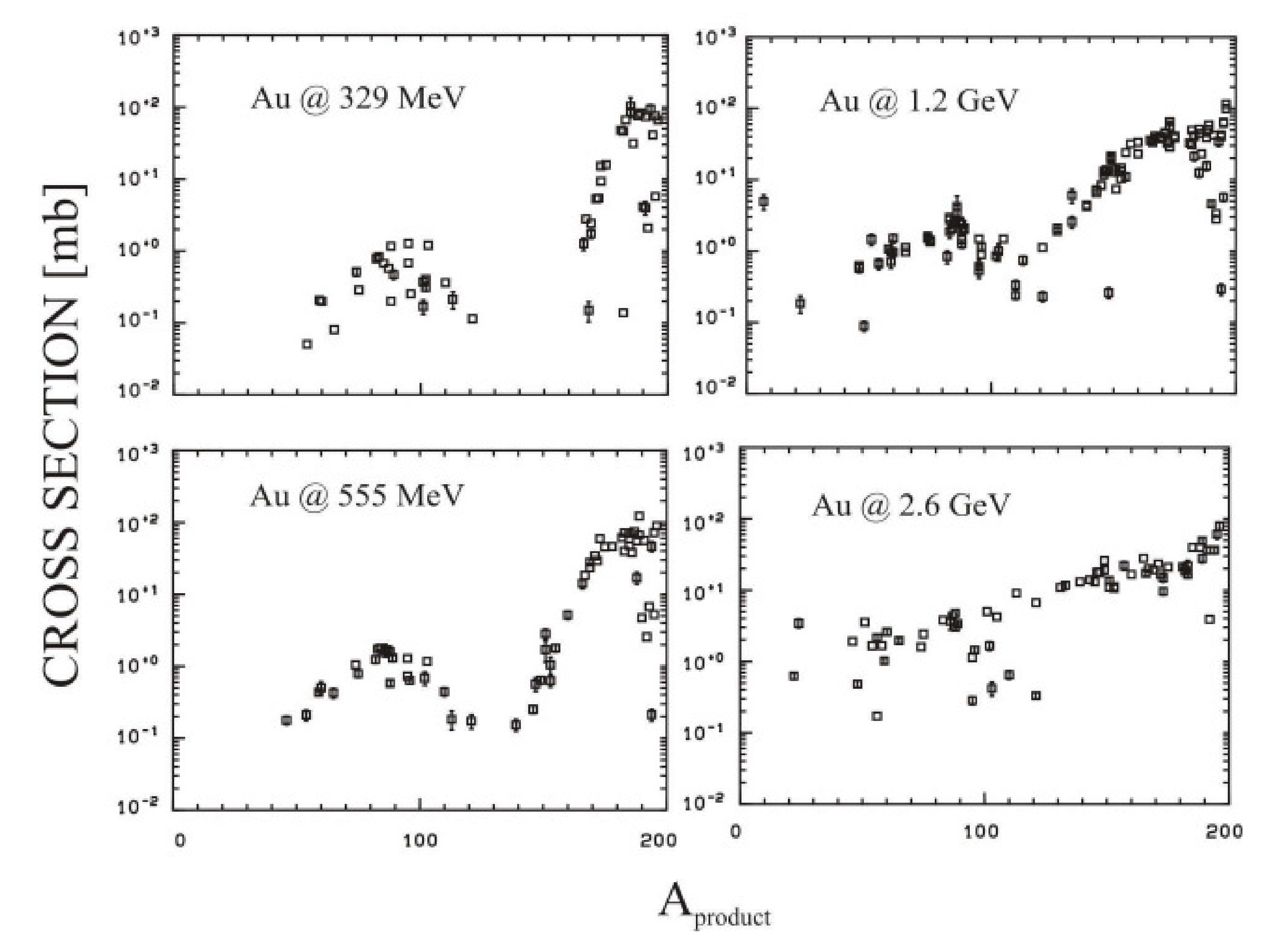


1E+04
1E+03
1E+02
1E+01
1E+00
1E-01
1E-02
CROSS SECTION in mb
1E+01
1E+02
1E+03
1E+04
PROTON ENERGY in MeV
Kuhnhenn
Gloris
TALYS
INCL4+ABLA

Nb(p,X) Isobaric Yields



Cross Sections versus Product Mass Numbers for Au(p,X)



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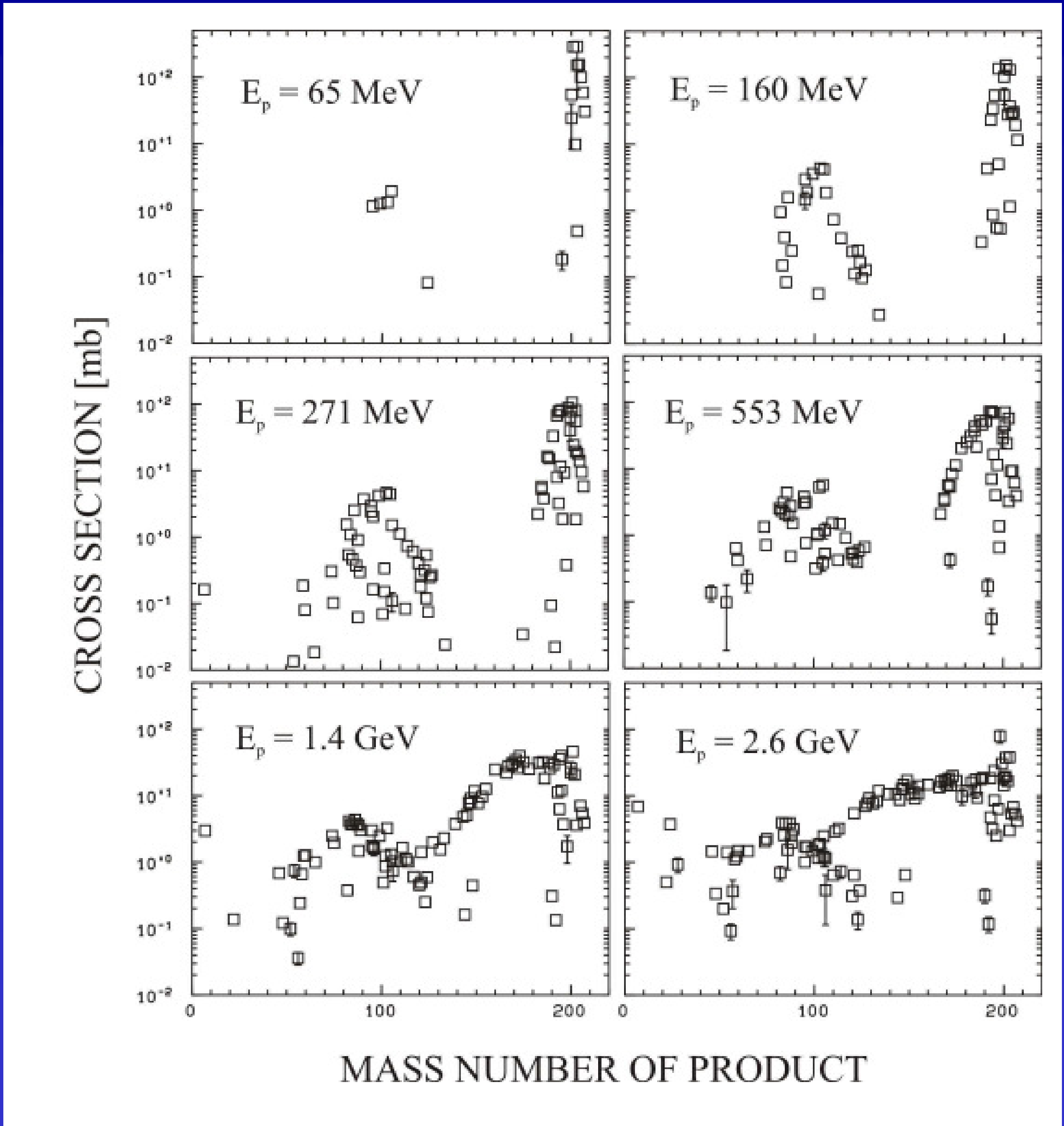

Cross sections versus product mass numbers for Pb(p,X)

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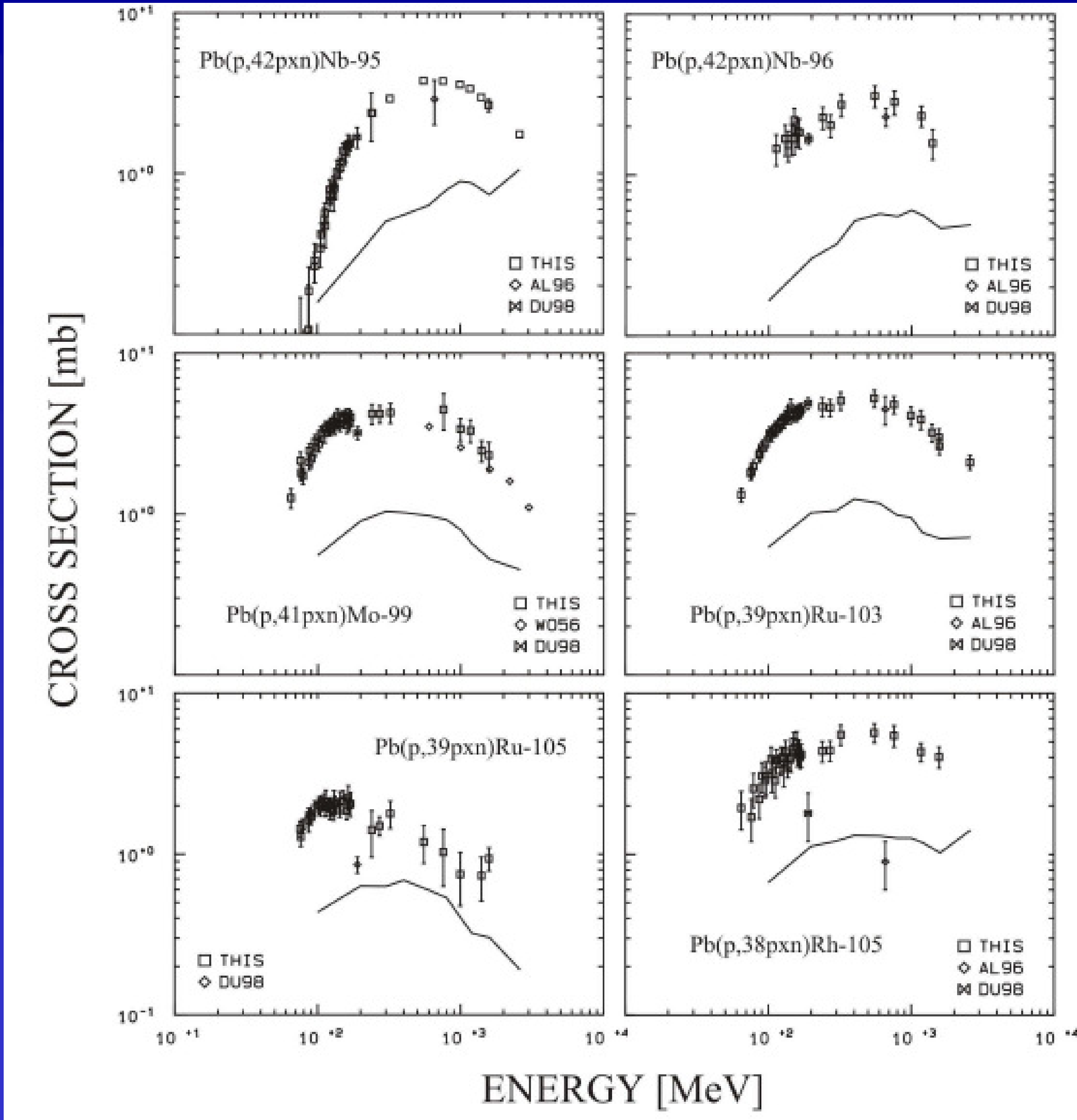
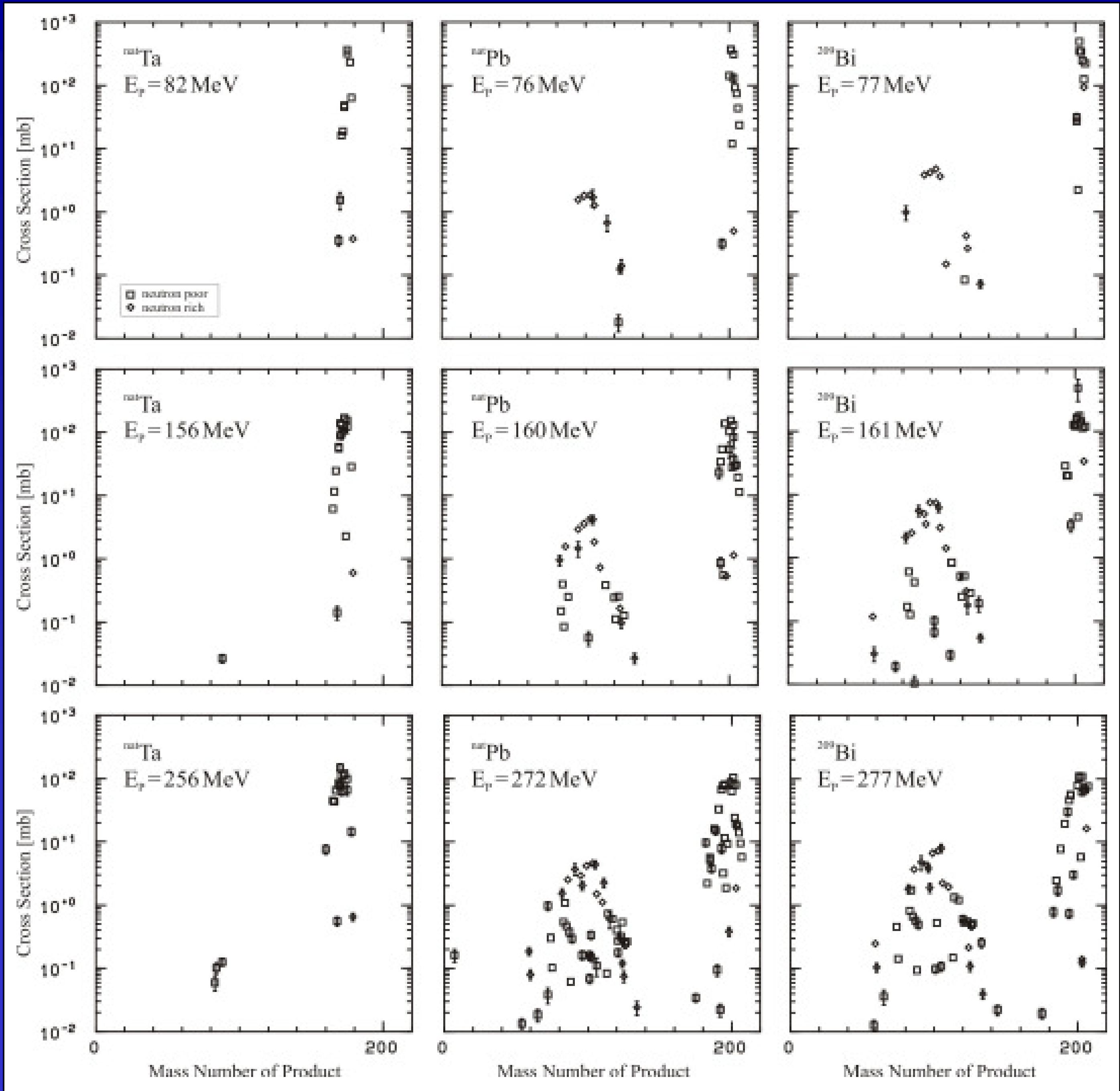


Medium energy fission of lead

Theory: LAHET code

Gloris et al. (2001)



Ta, Pb, Bi cross sections versus product mass numbers

76 – 300 MeV

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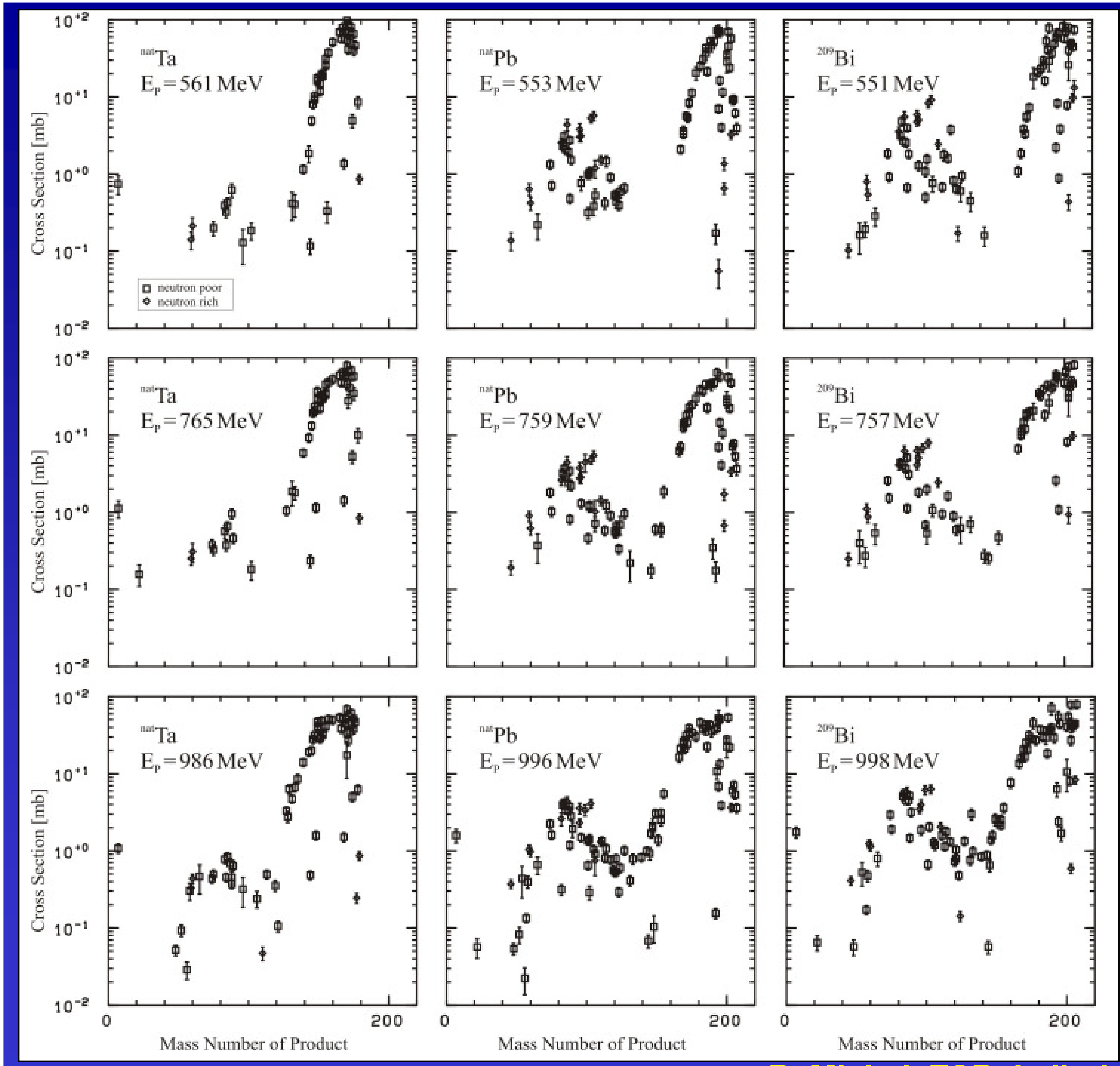

Ta, Pb, Bi cross sections versus product mass numbers

560 - 996 MeV

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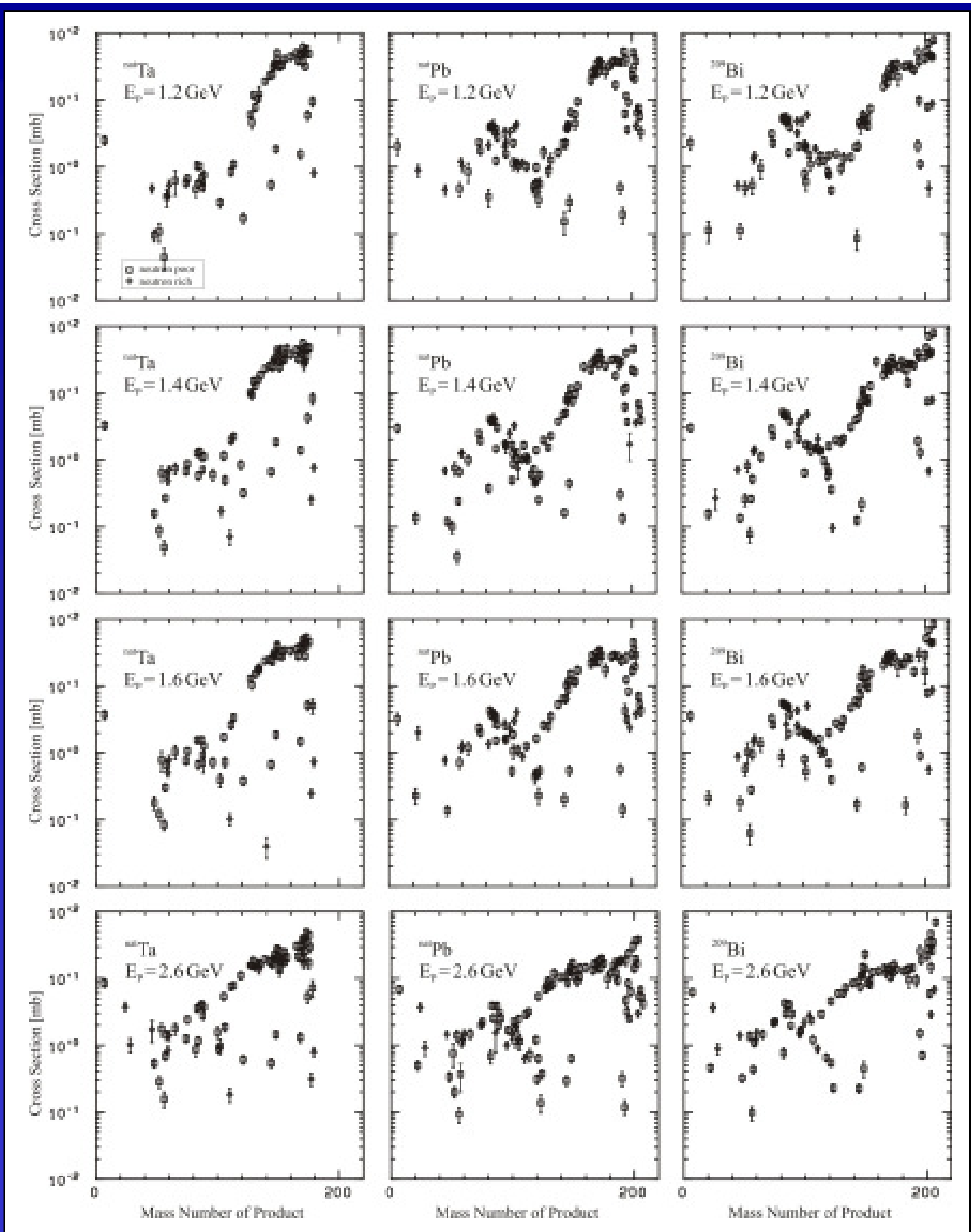

Ta, Pb, Bi cross sections versus product mass numbers

1.2 – 2.6 GeV

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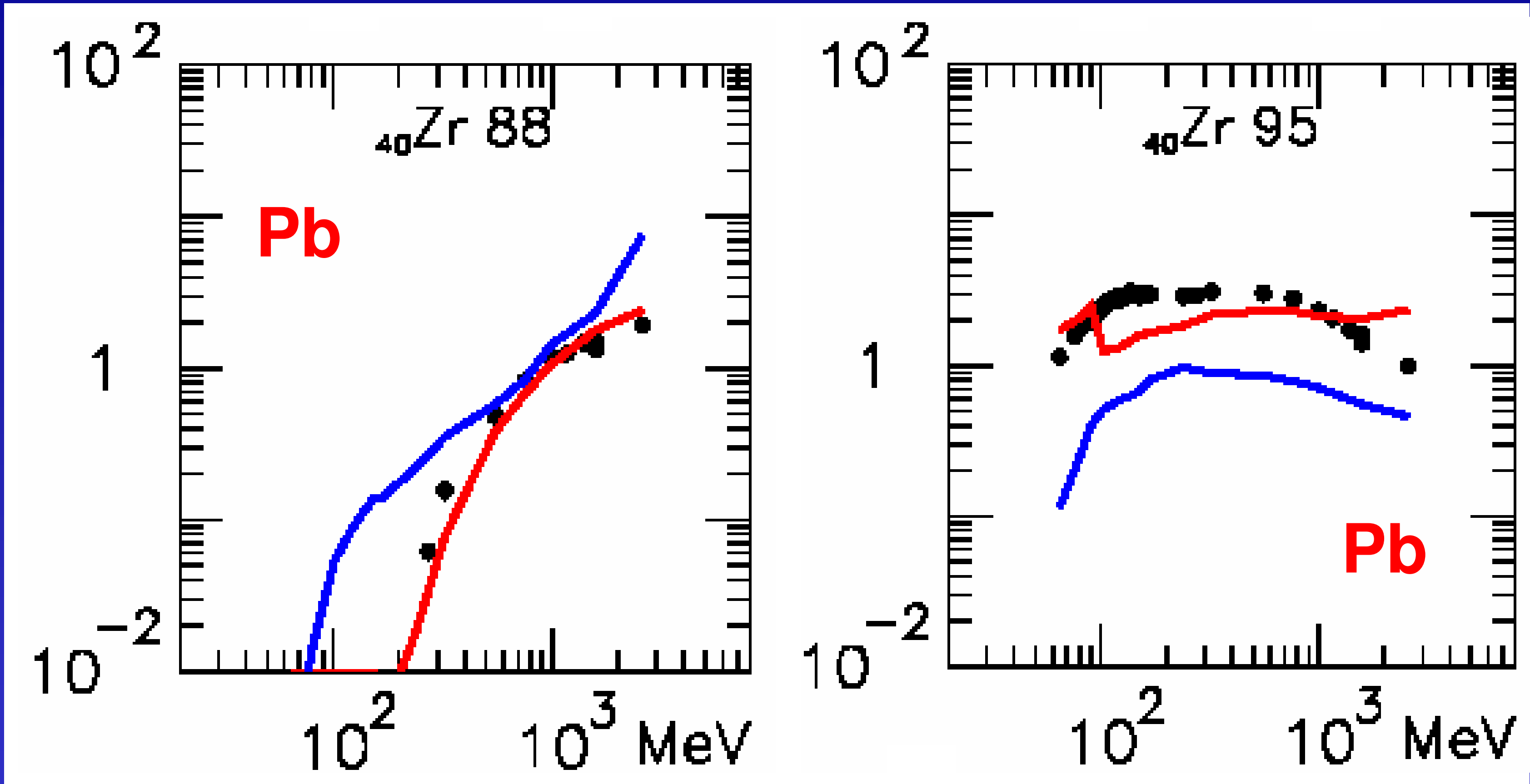
Production of ^{88}Zr and ^{95}Zr from Lead



INCL4 + ABLA

Bertini-Dresner-PE

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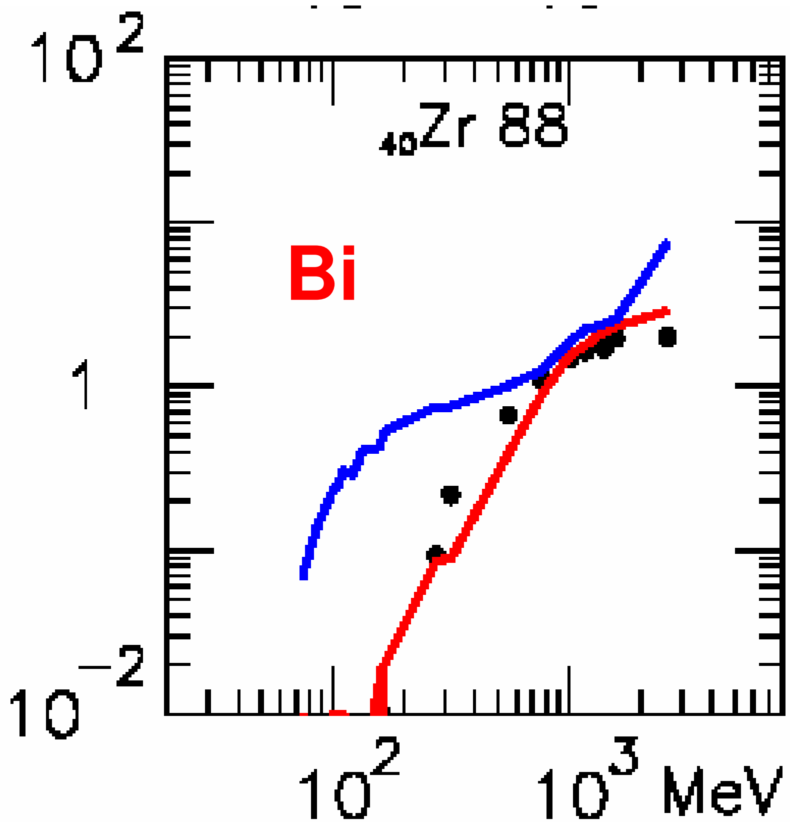
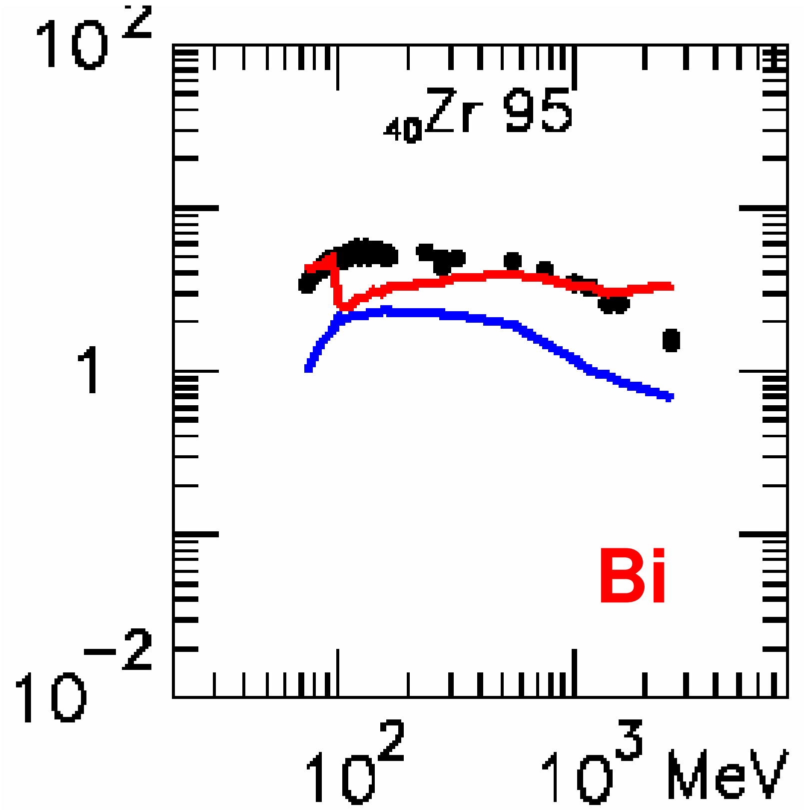
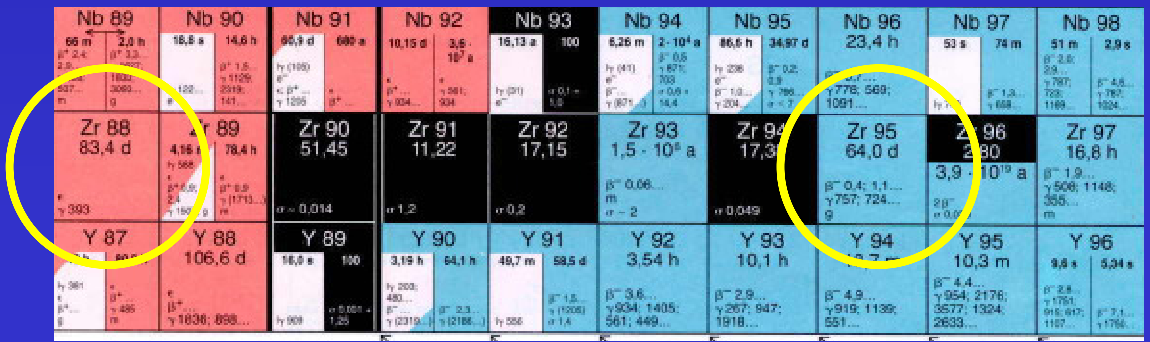
Production of ^{88}Zr and ^{95}Zr from Bismuth







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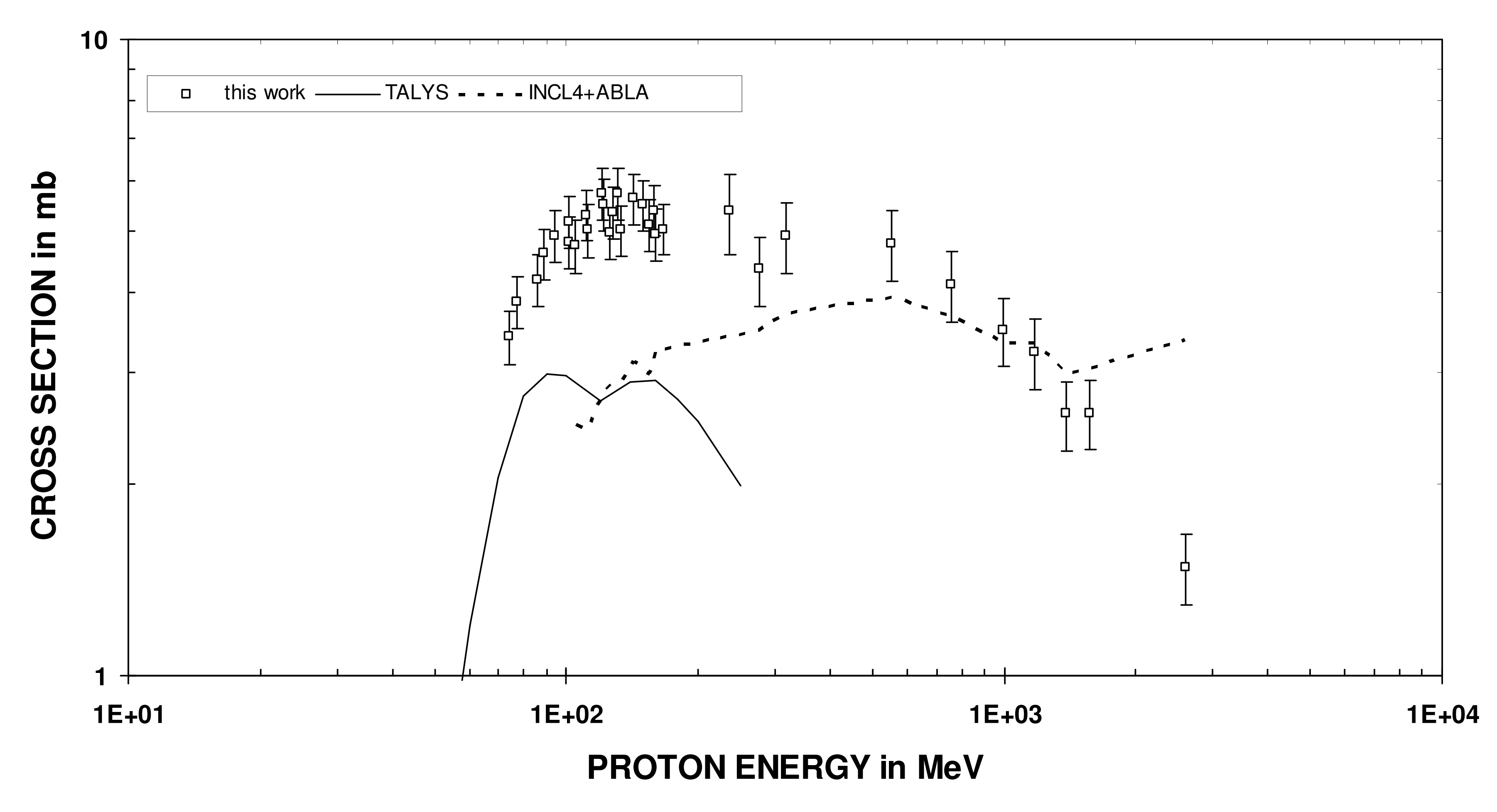
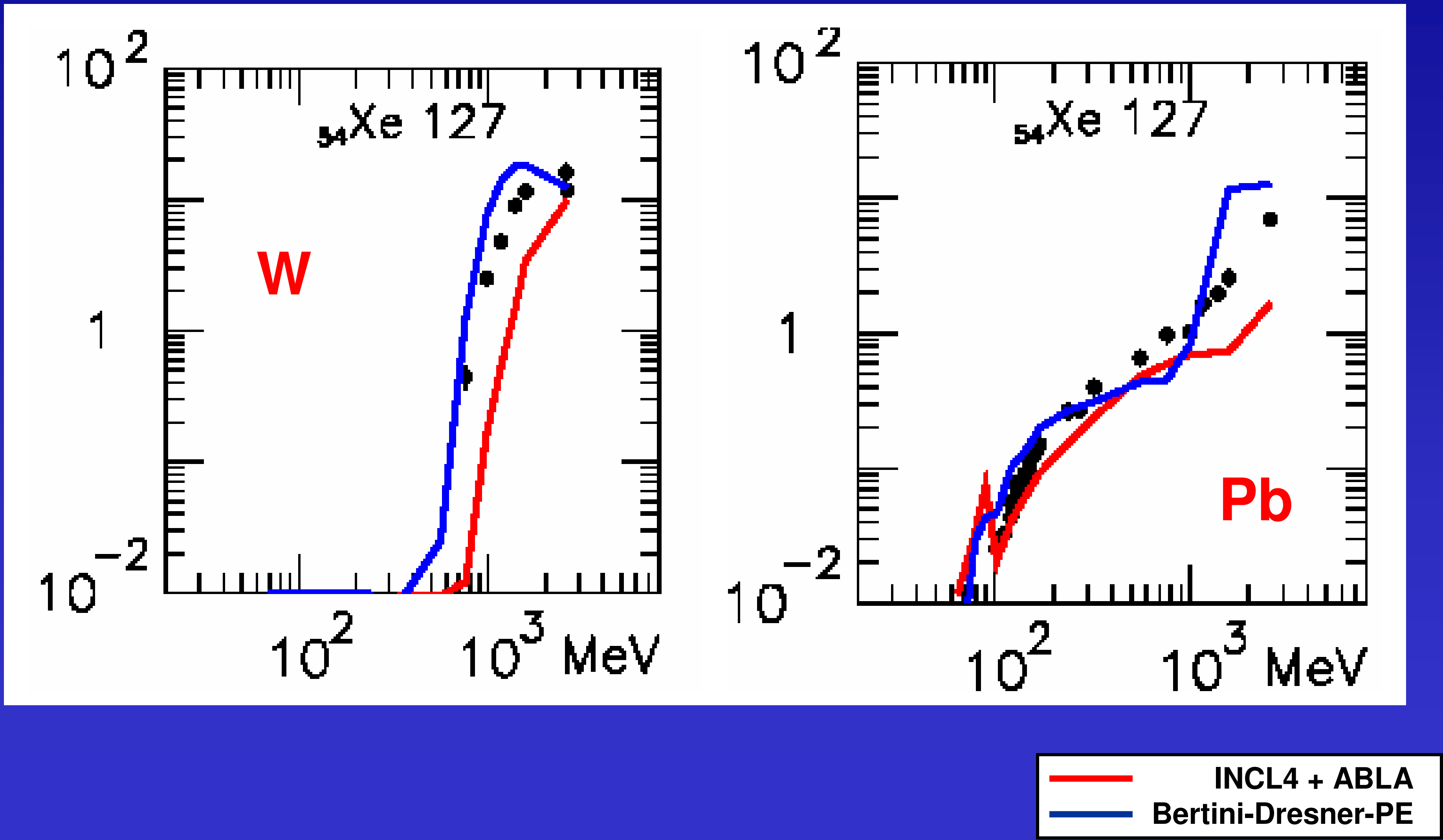
Bi-209(p,f)Zr-95



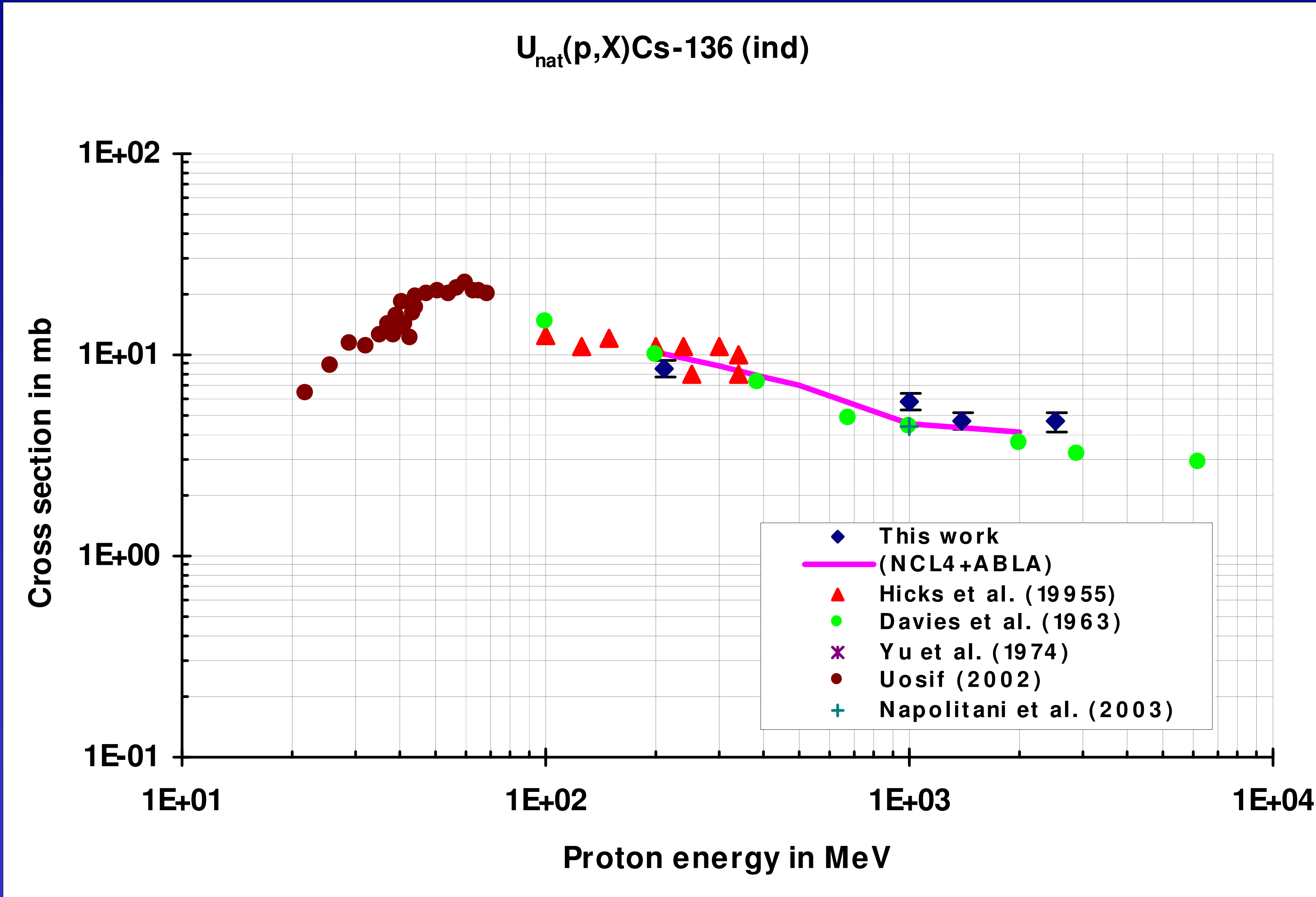
Uosif et al. (2004)

Production of ^{127}Xe



R. Michel, ZSR, Leibniz Universität Hannover

Proton-induced reactions on Uranium



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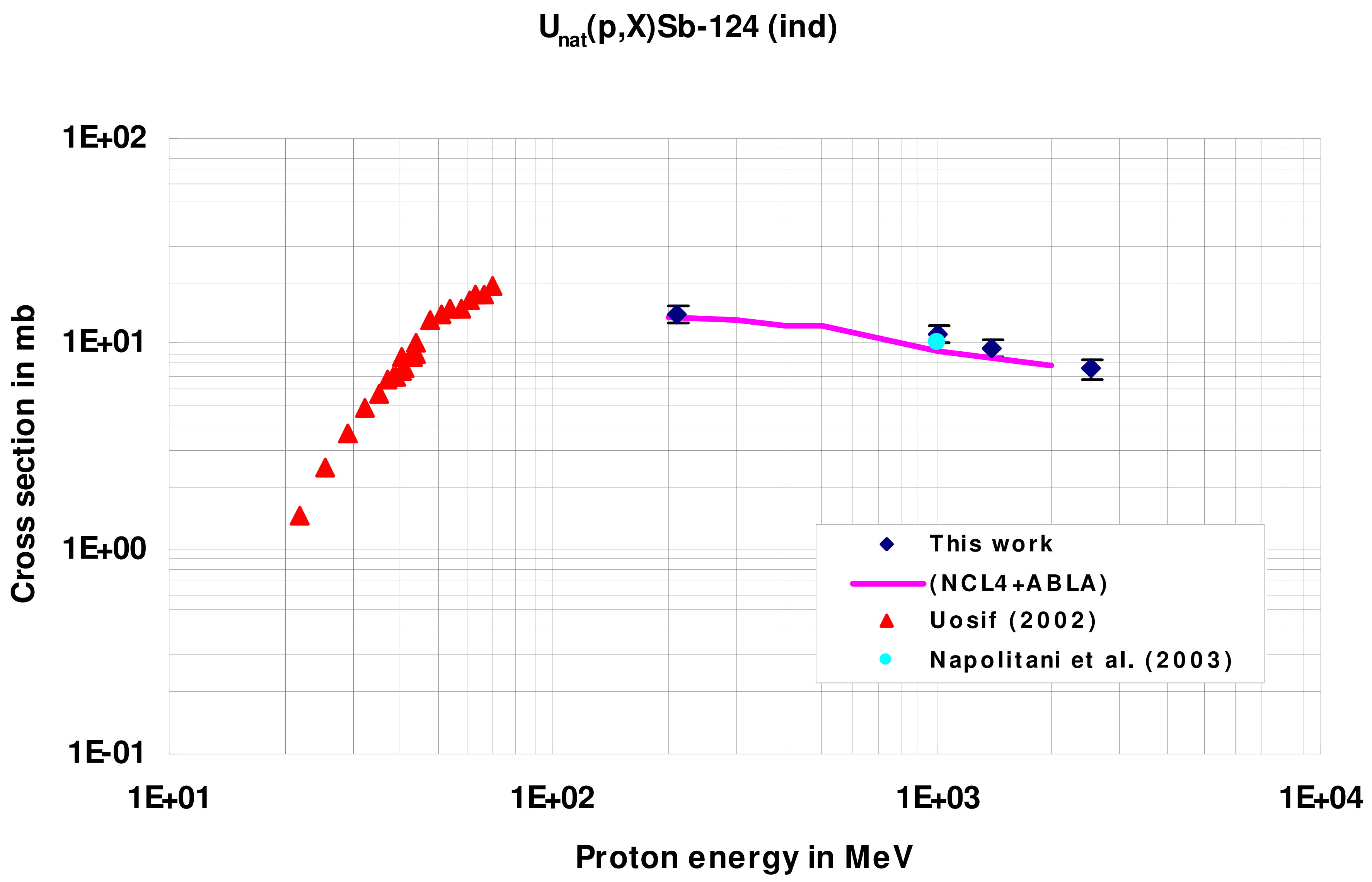
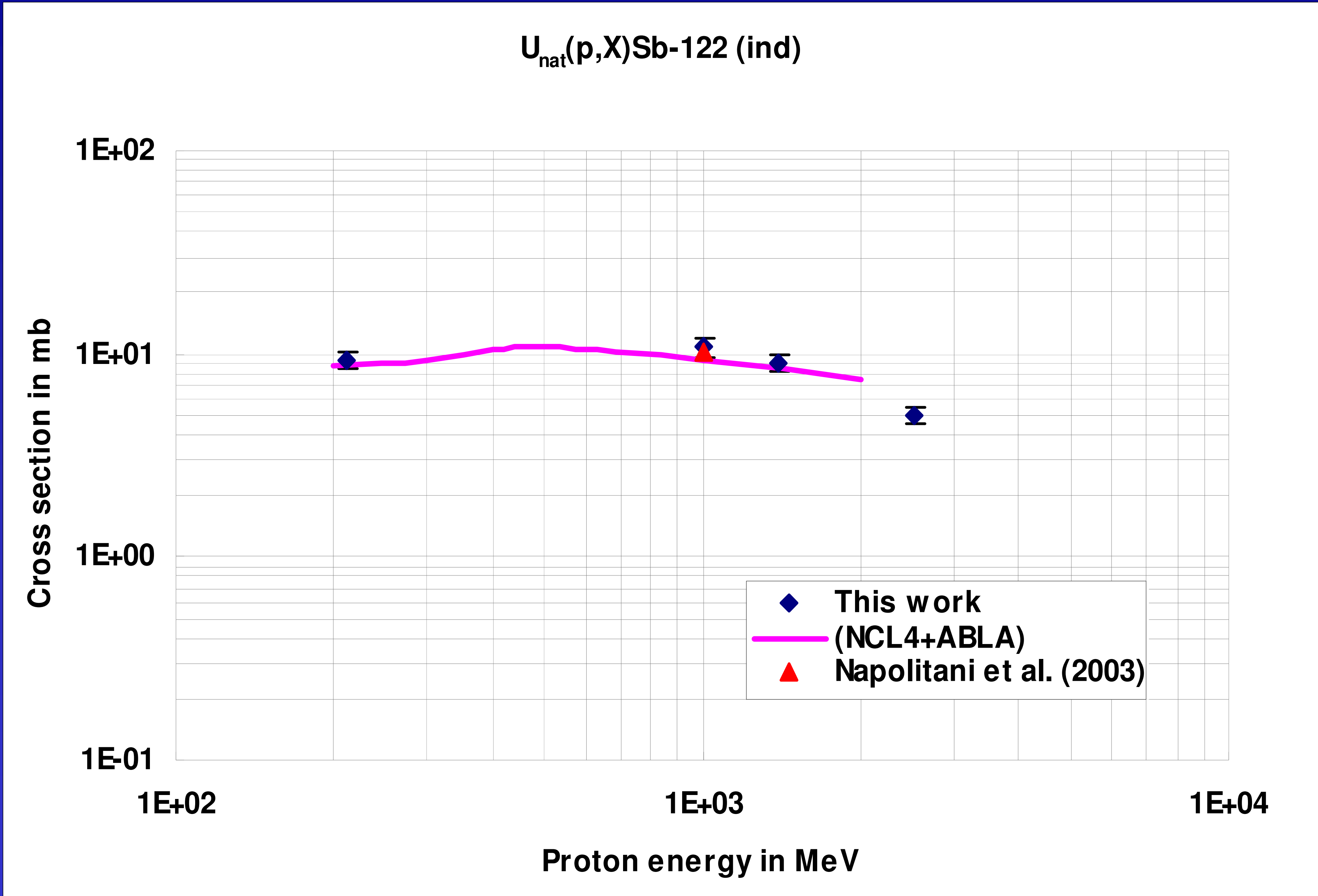
Proton-induced reactions on Uranium



Proton-induced reactions on Uranium



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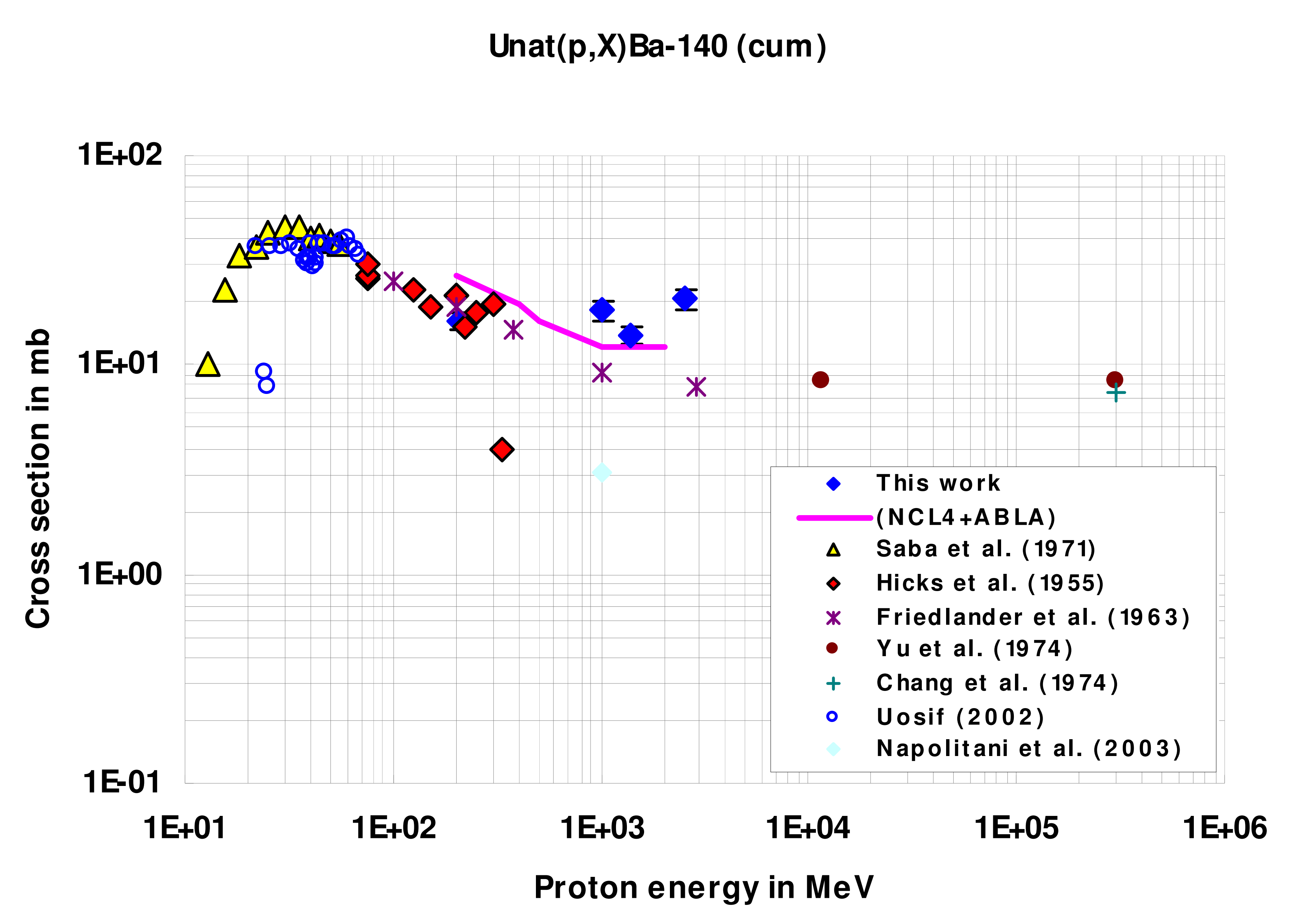
Proton-induced reactions on Uranium



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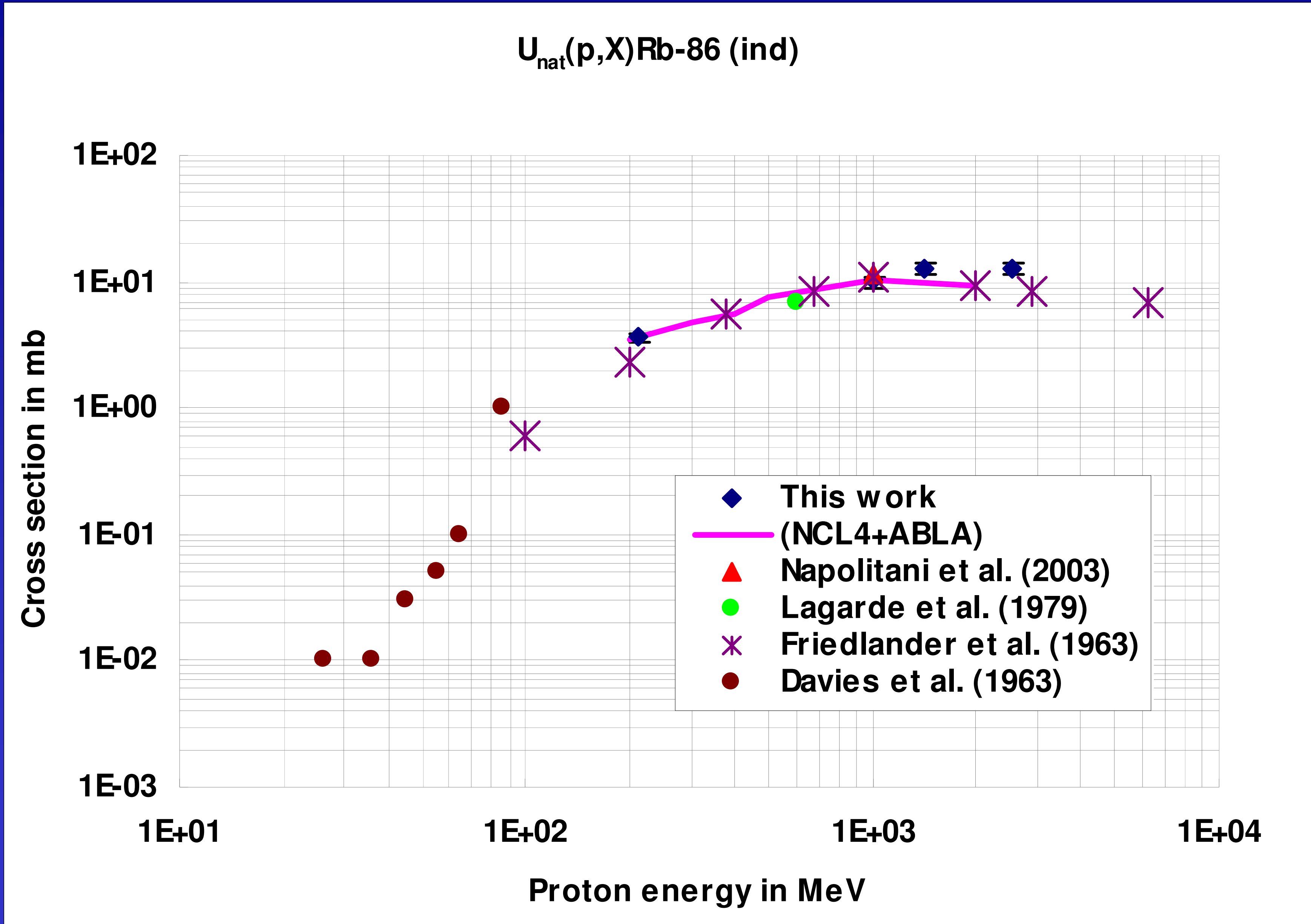
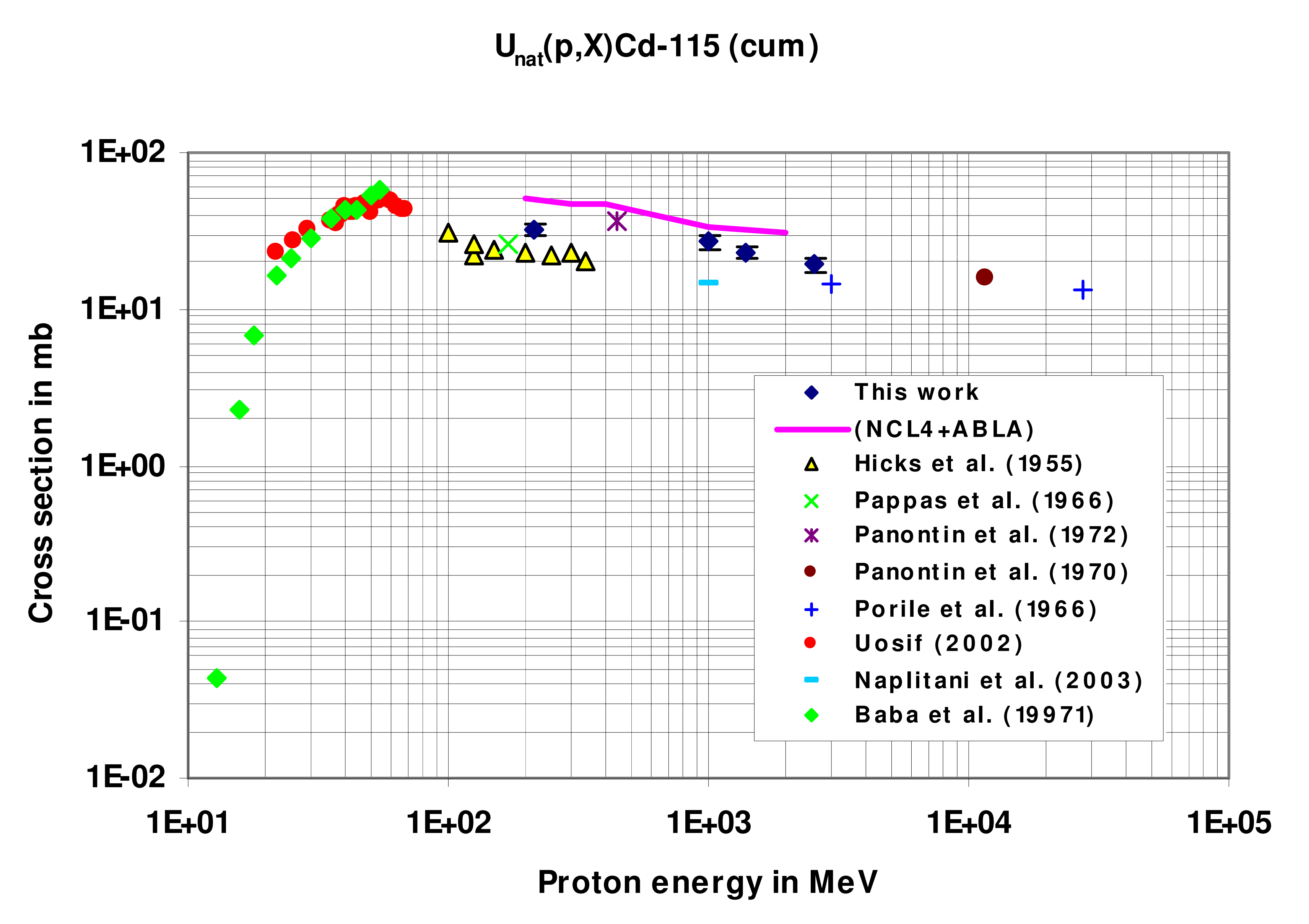
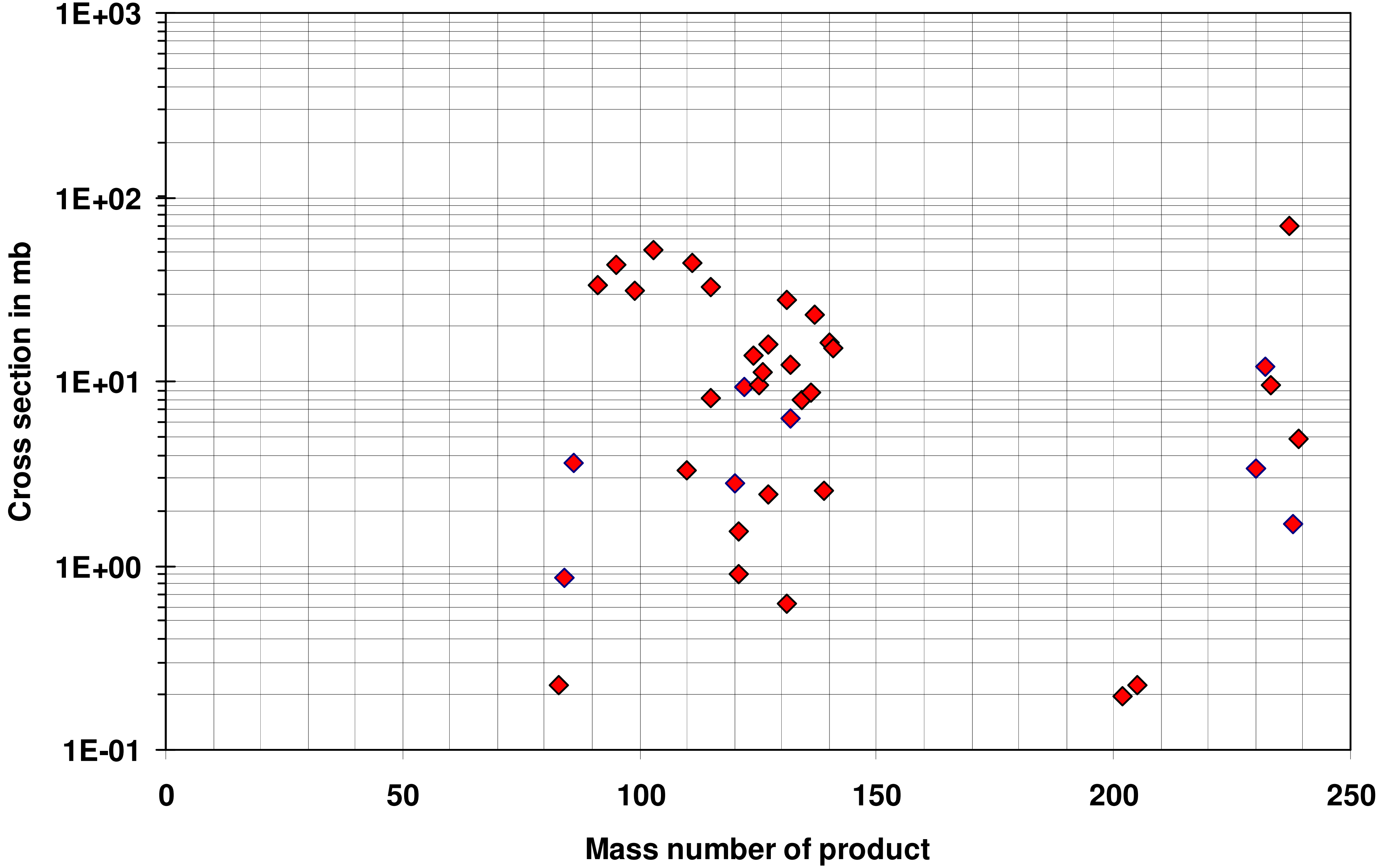
Proton-induced reactions on Uranium

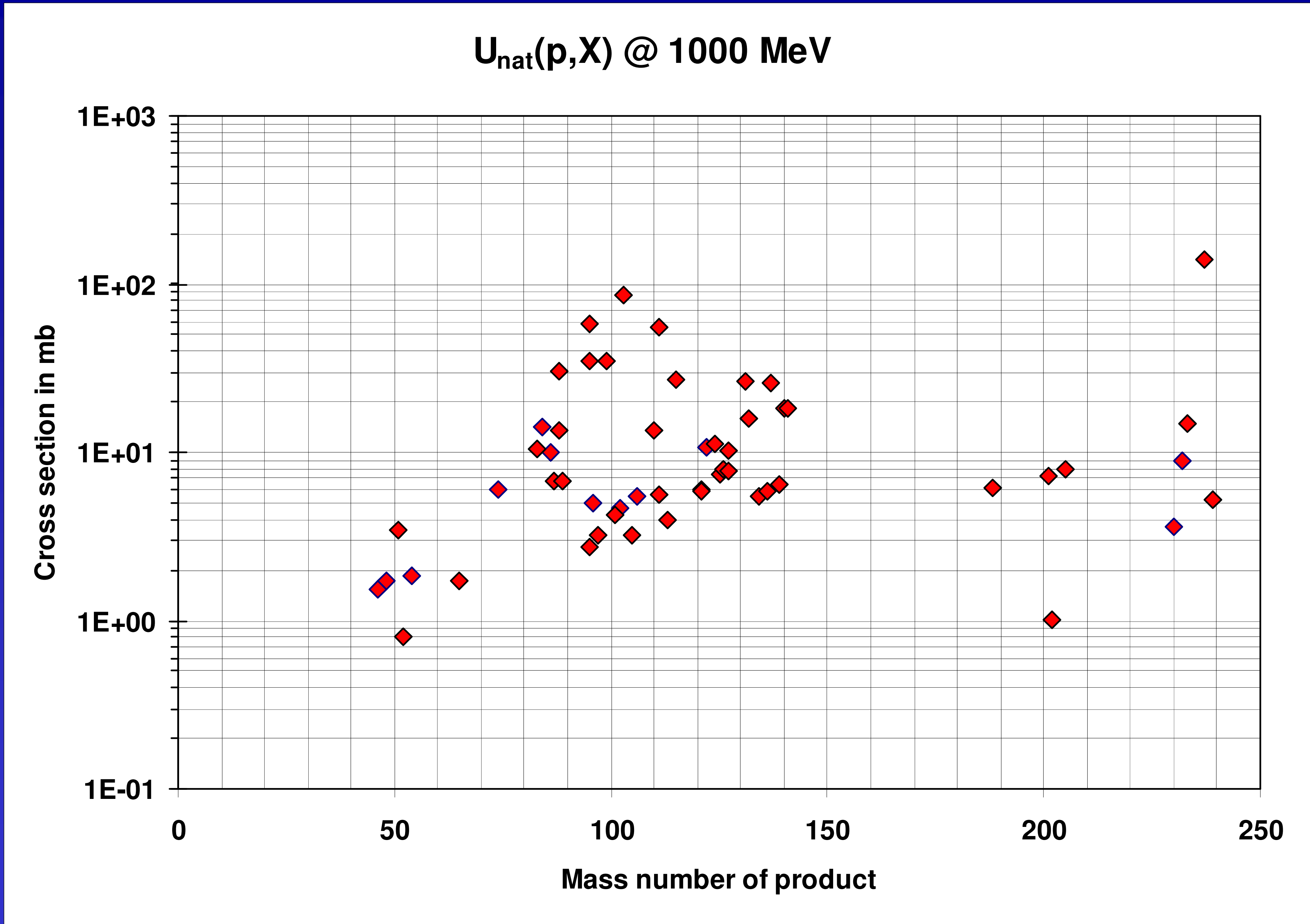


Proton-induced reactions on Uranium



$U_{nat}(p,X)$ @ 211 MeV





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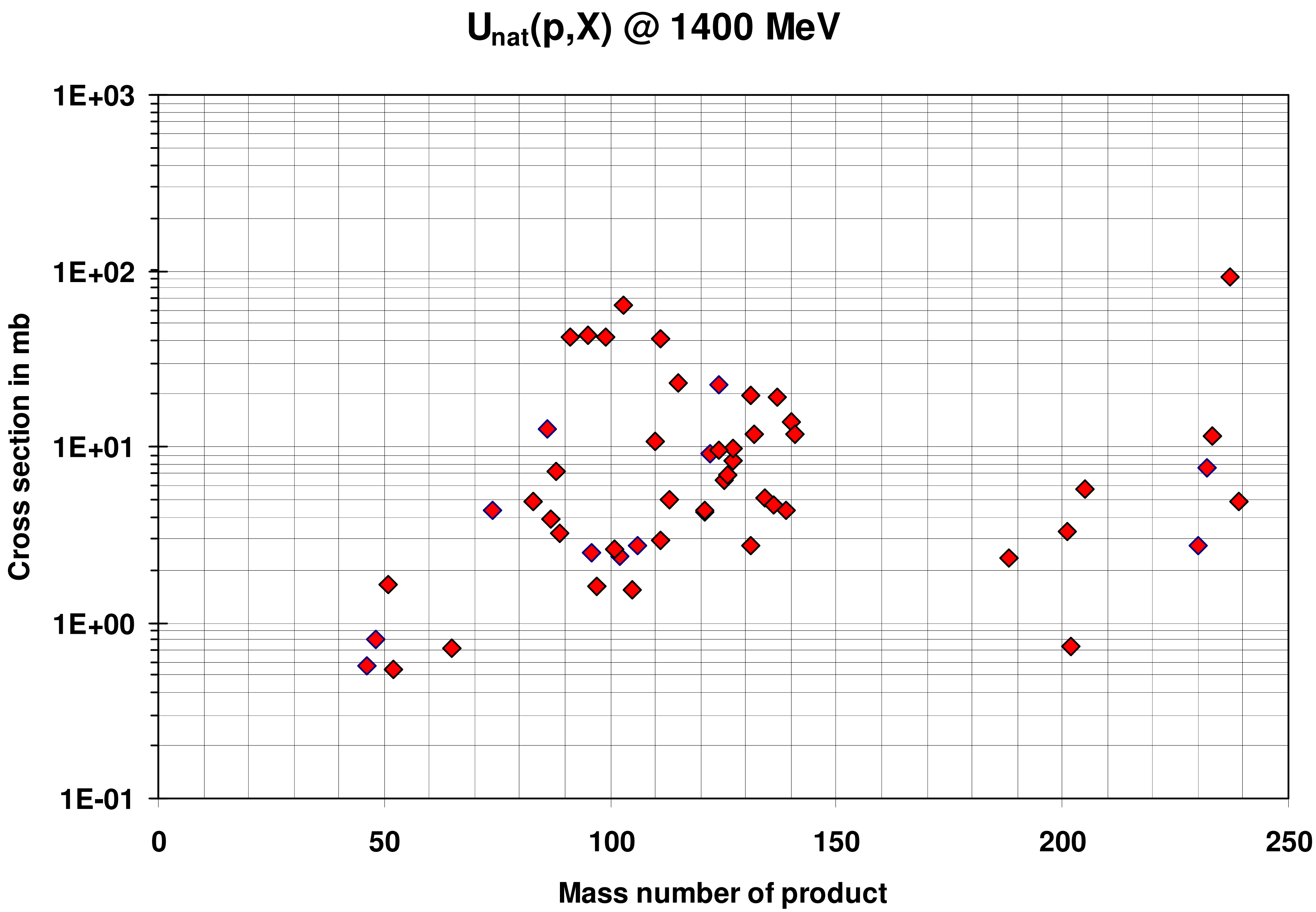

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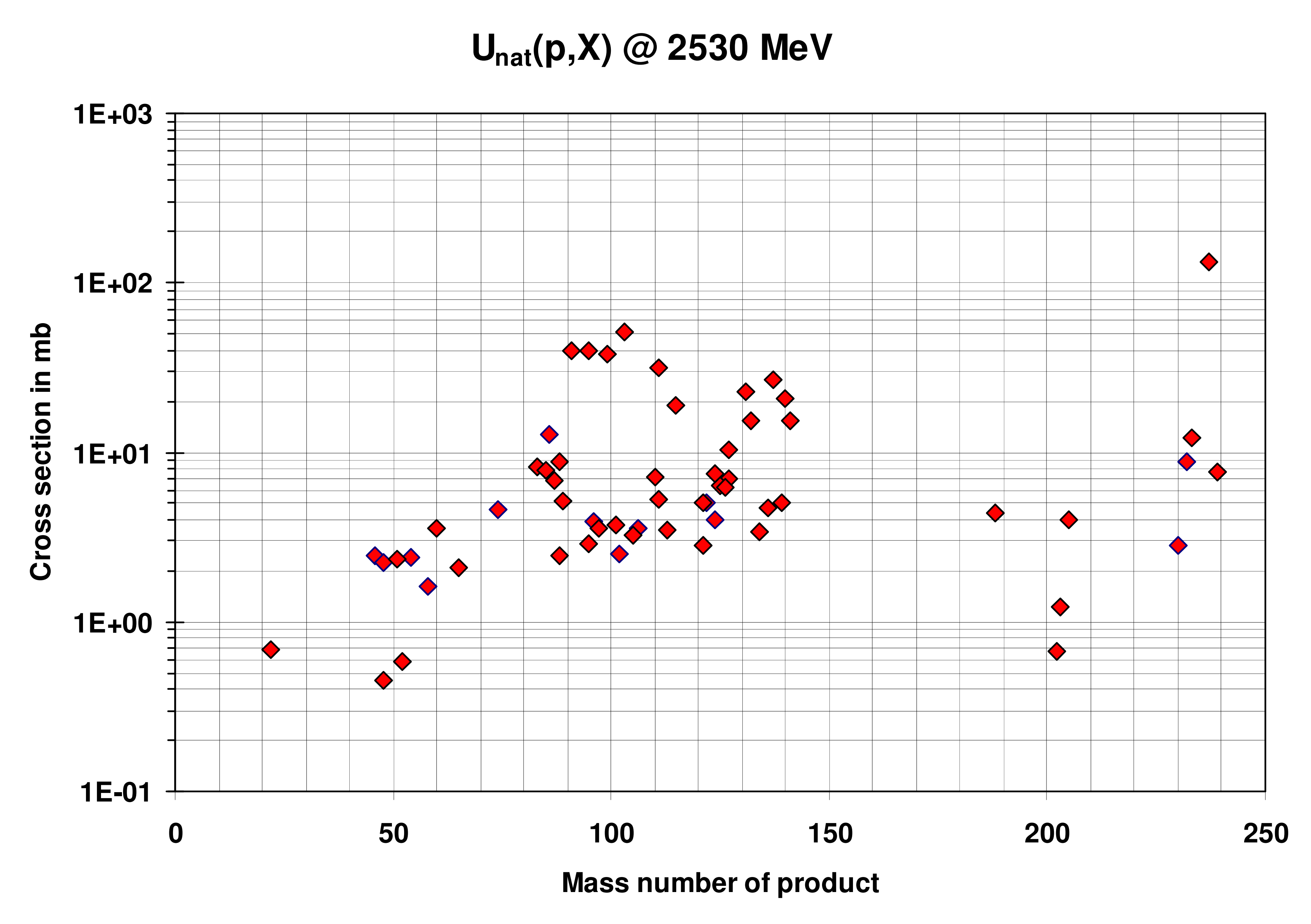

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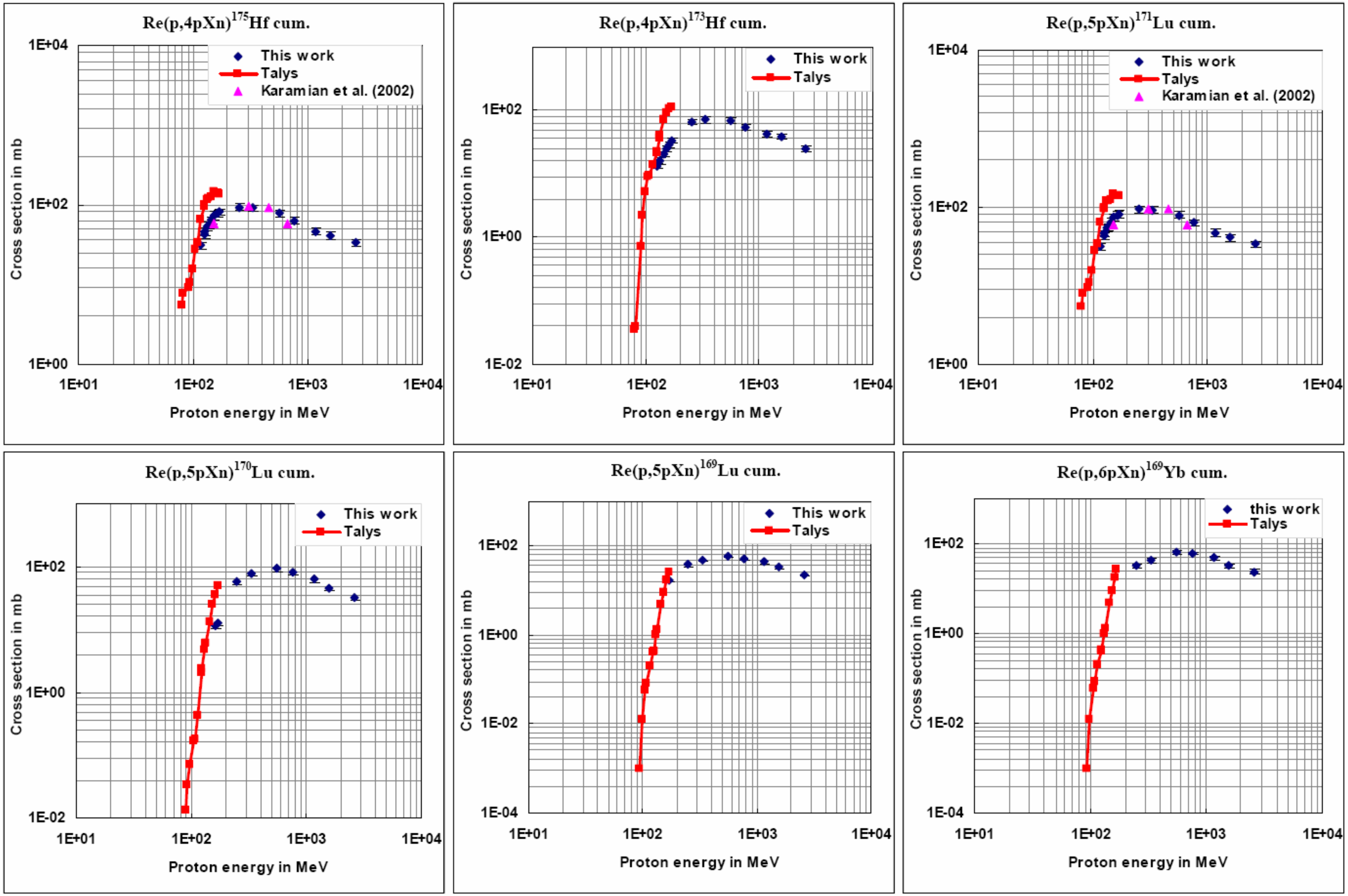
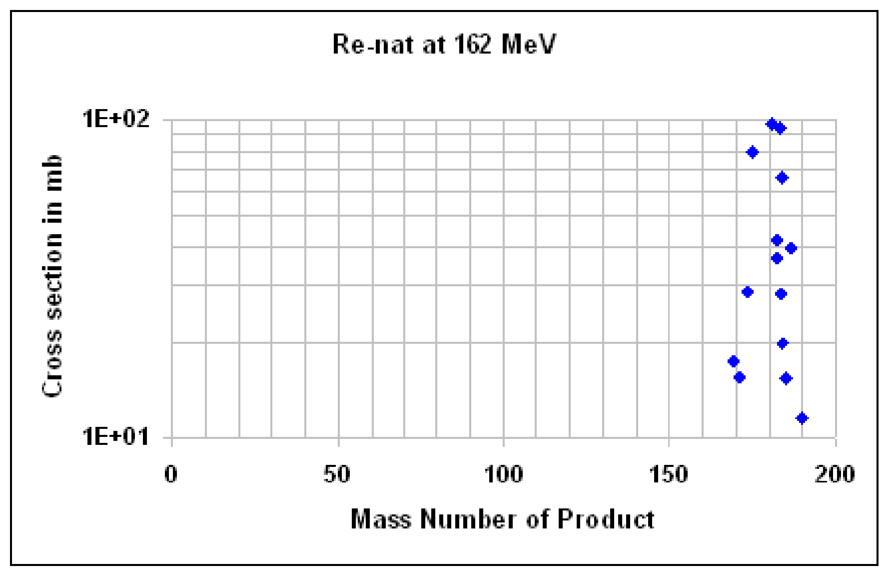
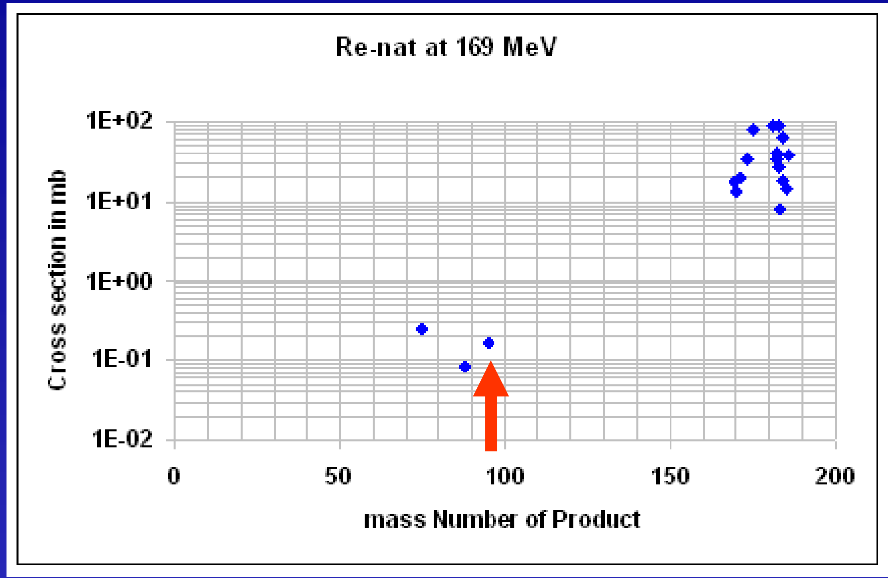
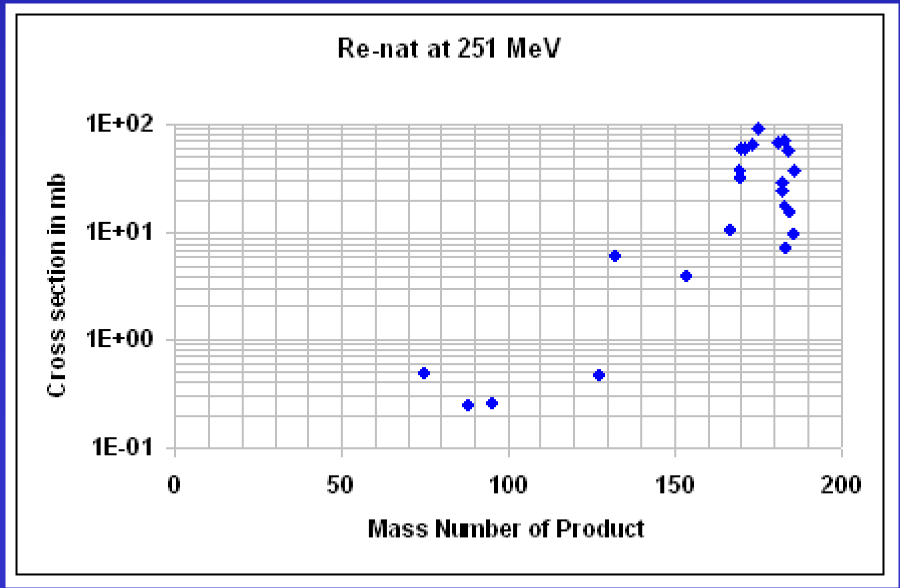
Proton-induced reactions on Rhenium

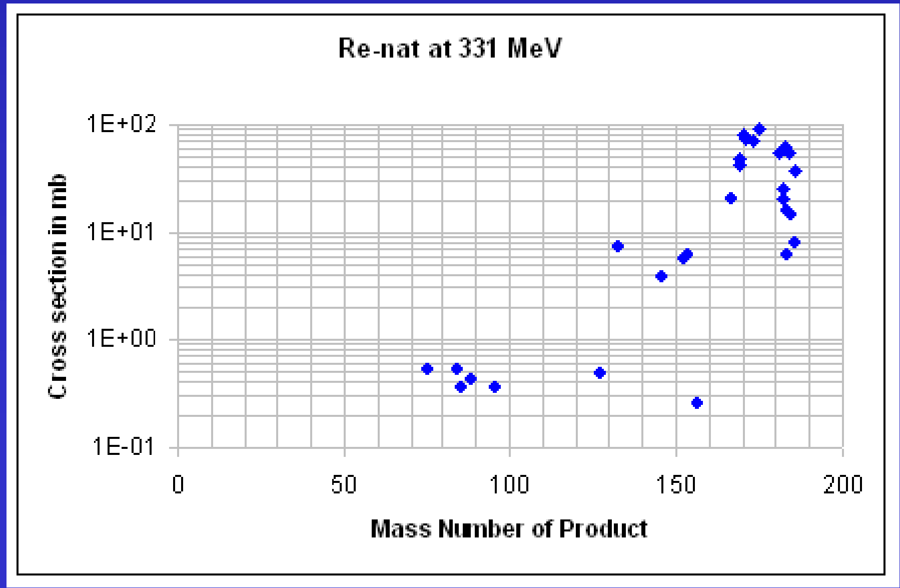


Proton-Induced Reactions on Rhenium









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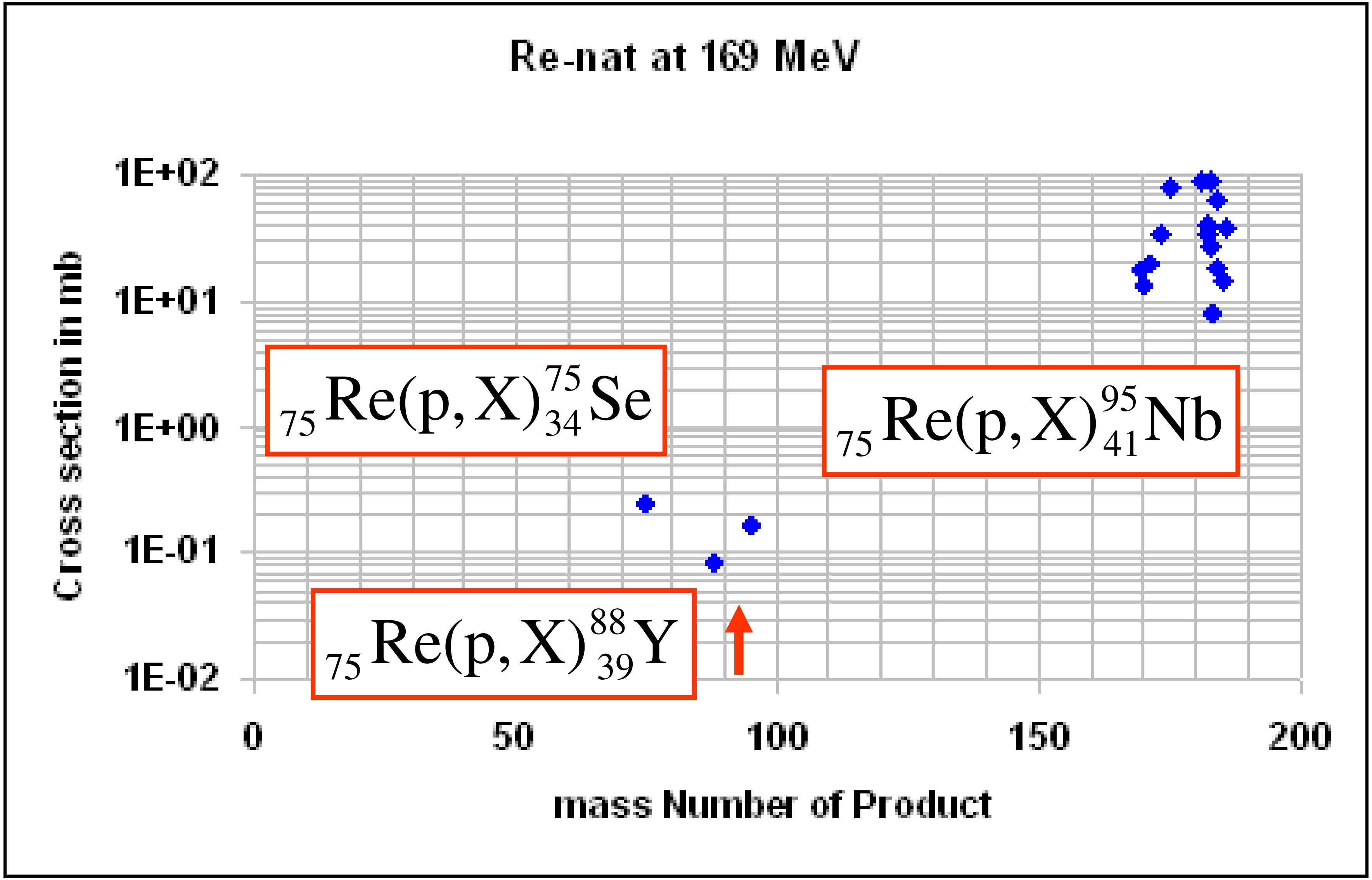
Proton-Induced Reactions on Rhenium



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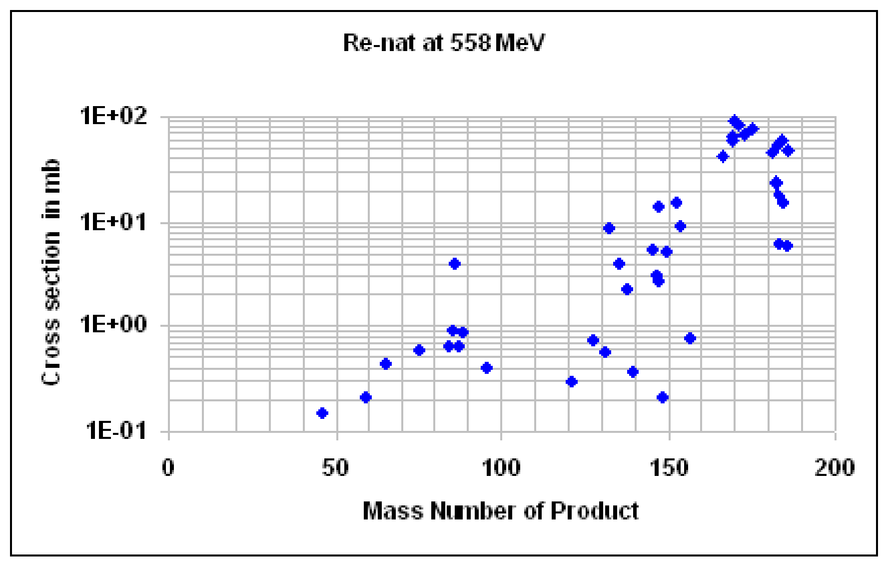
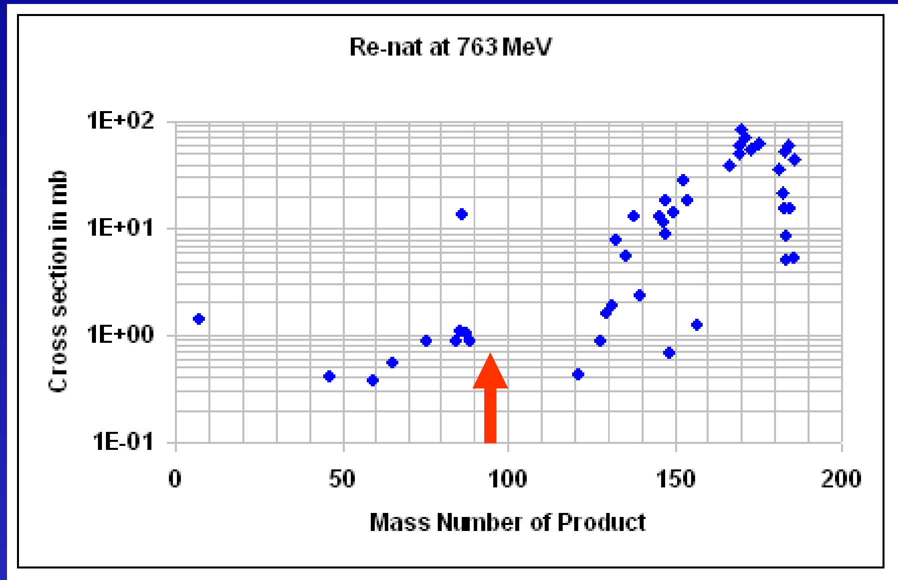
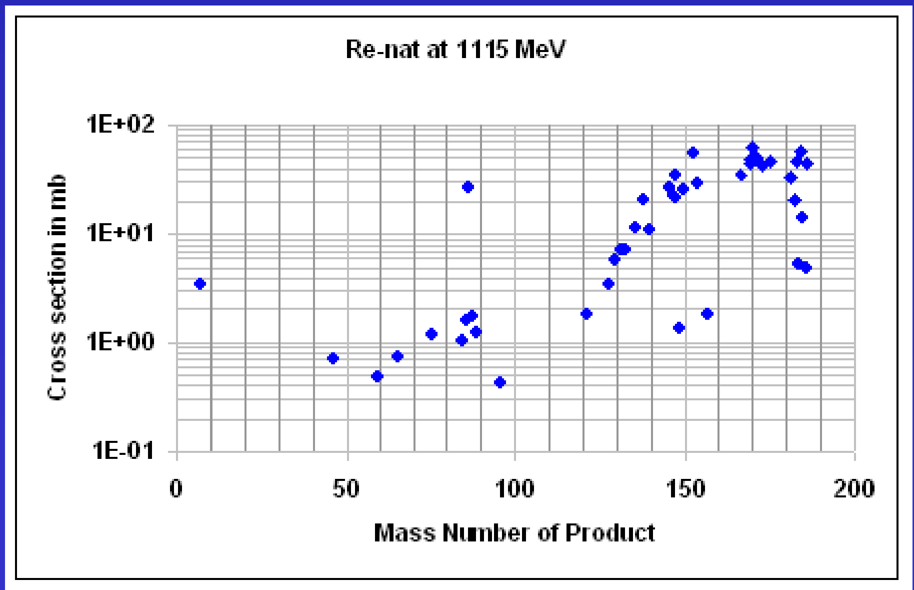
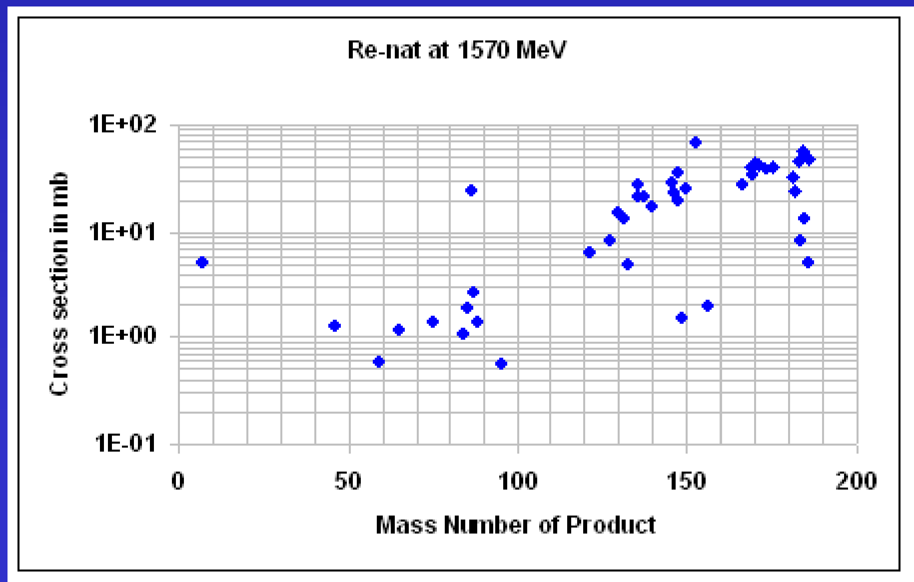
Proton-Induced Reactions on Rhenium









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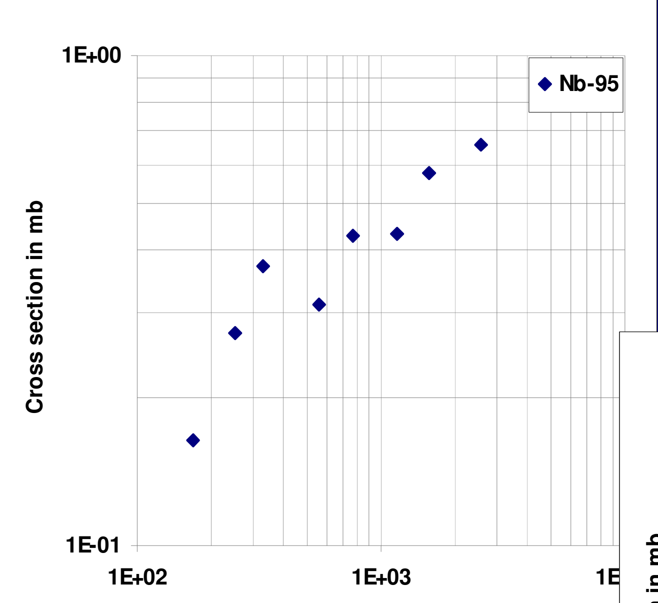
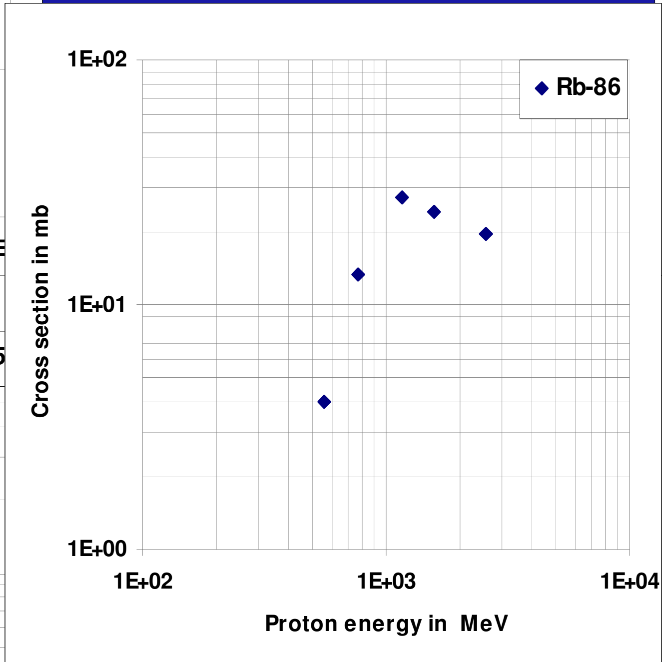
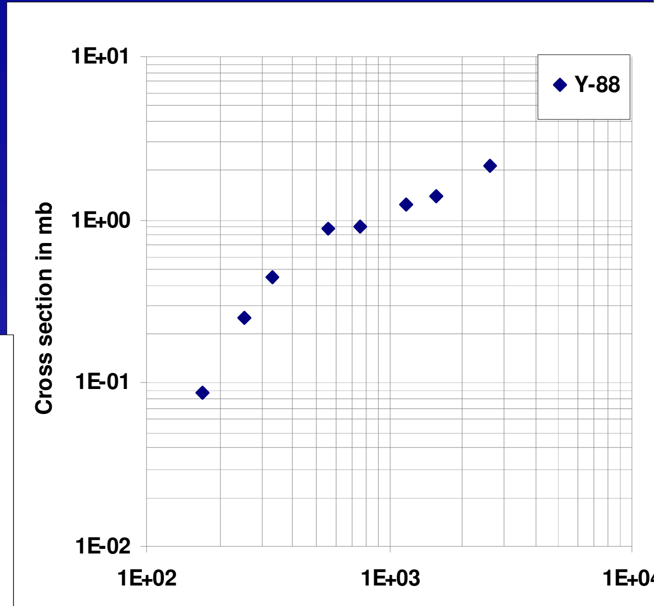
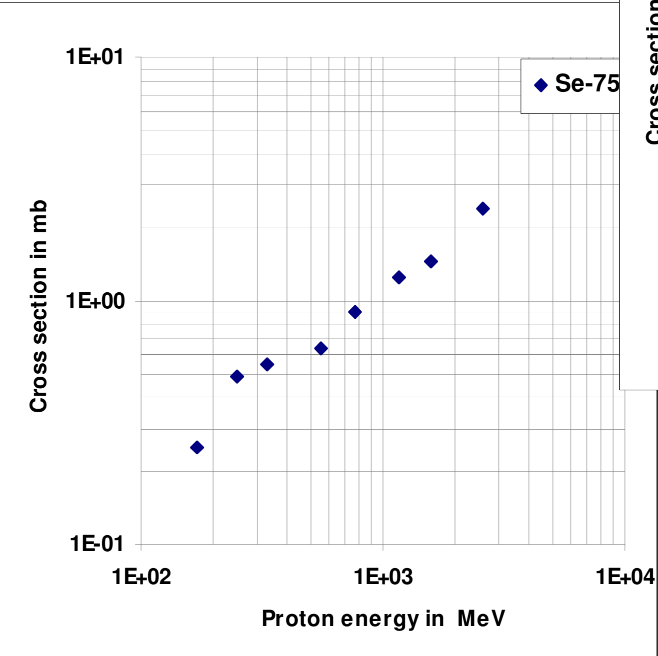
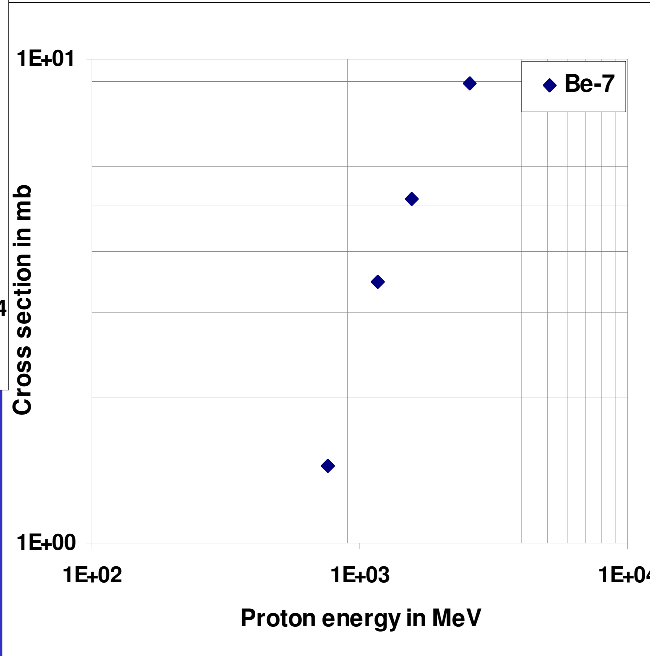
Proton-Induced Reactions on Rhenium











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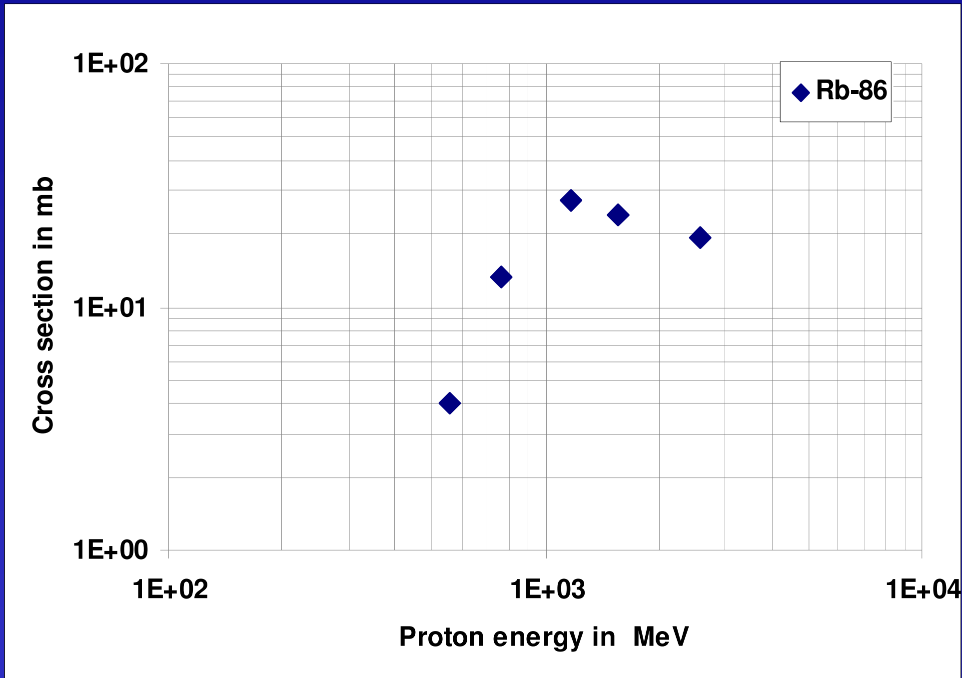
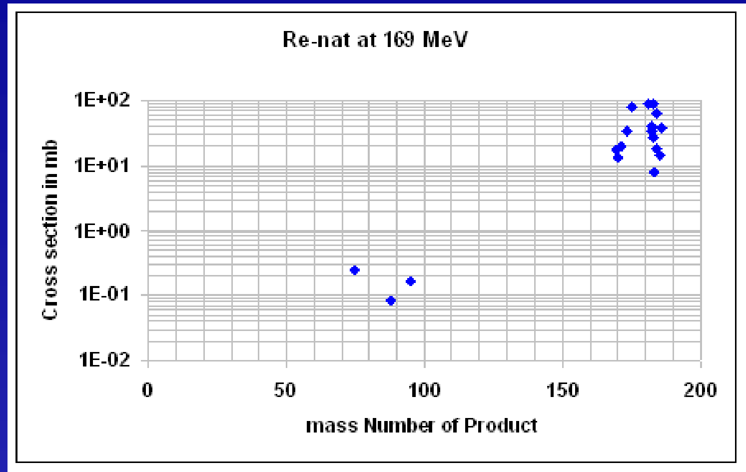
Special Reactions on Rhenium

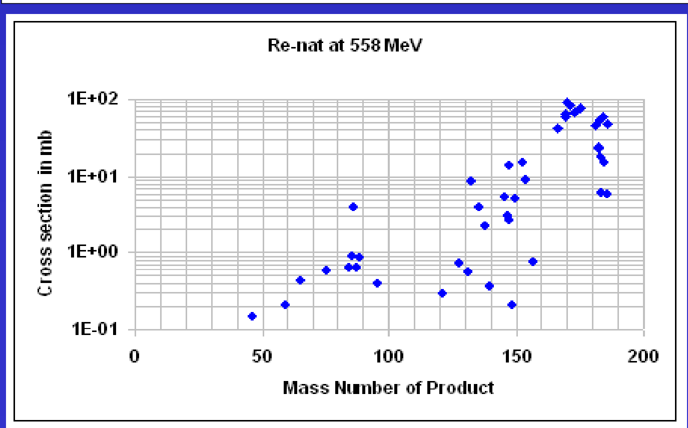
$_{75}\mathrm{Re(p,X)}^{86}_{37}\mathrm{Rb}$ ind.





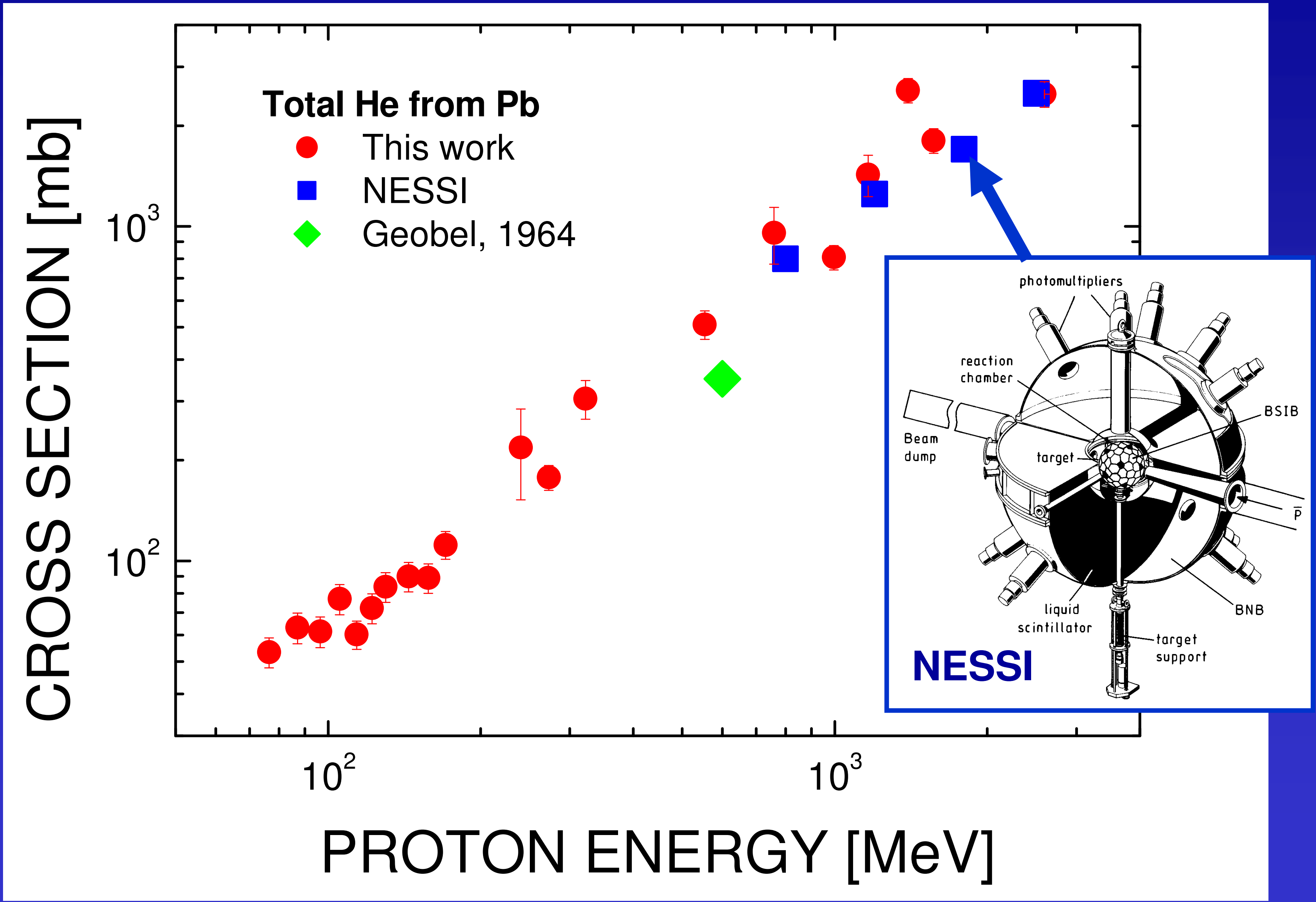
$_{75}\mathrm{Re(p,X)}^{95}_{41}\mathrm{Nb}$ cum.

$_{75}\mathrm{Re(p,X)}^{88}_{39}\mathrm{Y}$ cum.



$_{75}\mathrm{Re(p,X)}^{75}_{34}\mathrm{Se}$ cum.

Production of Helium from Lead



Leya et al. (2004)

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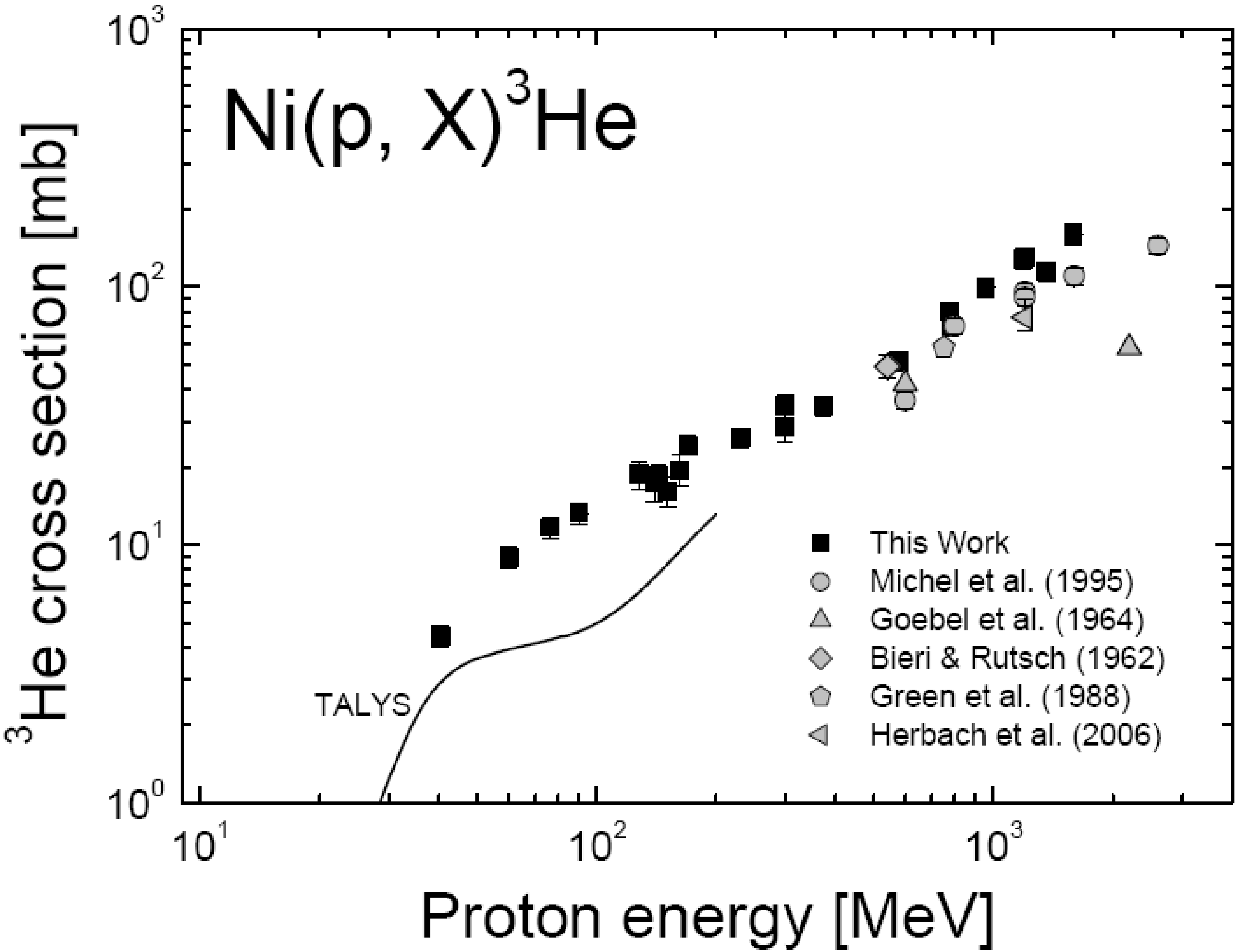
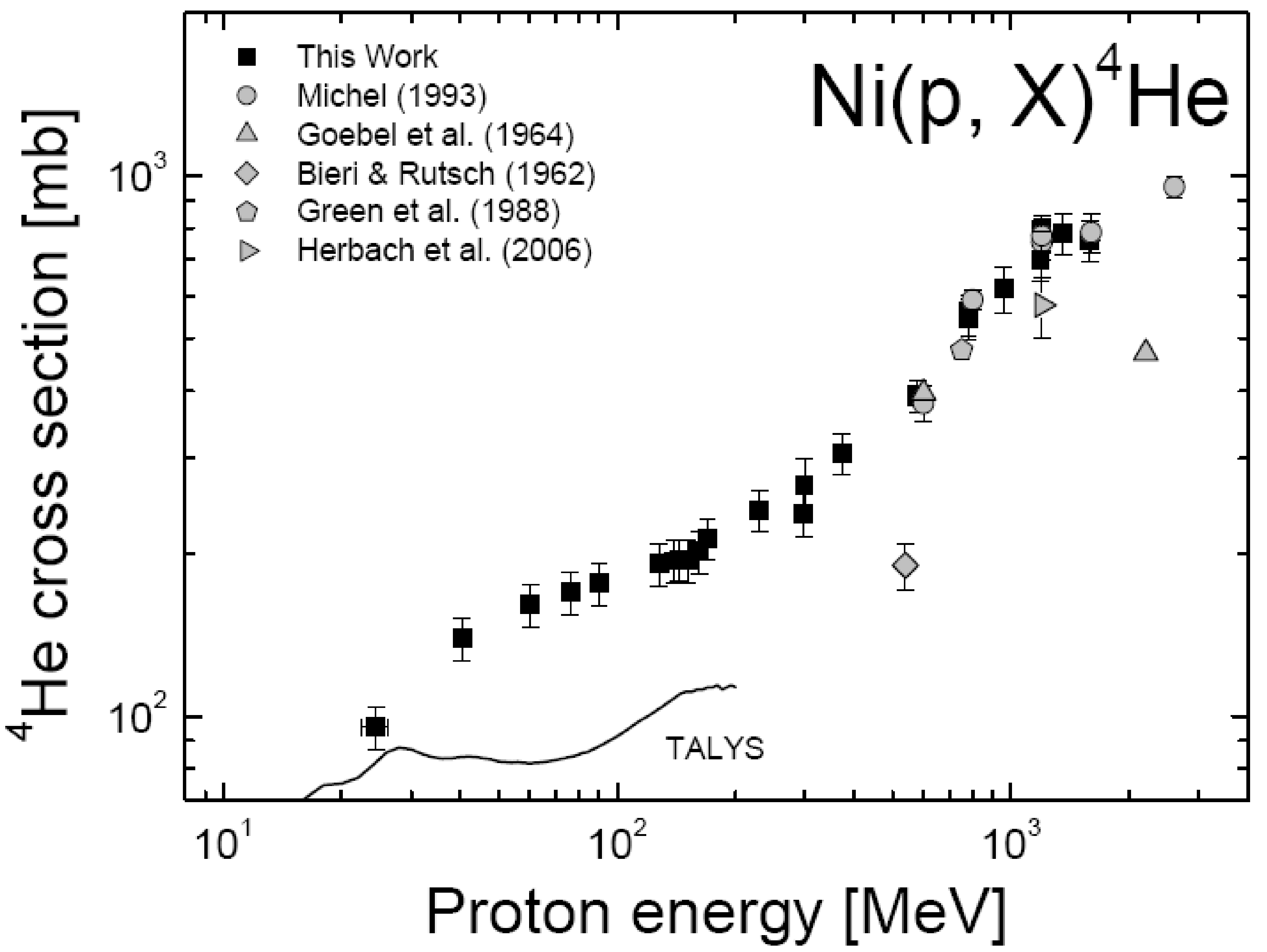
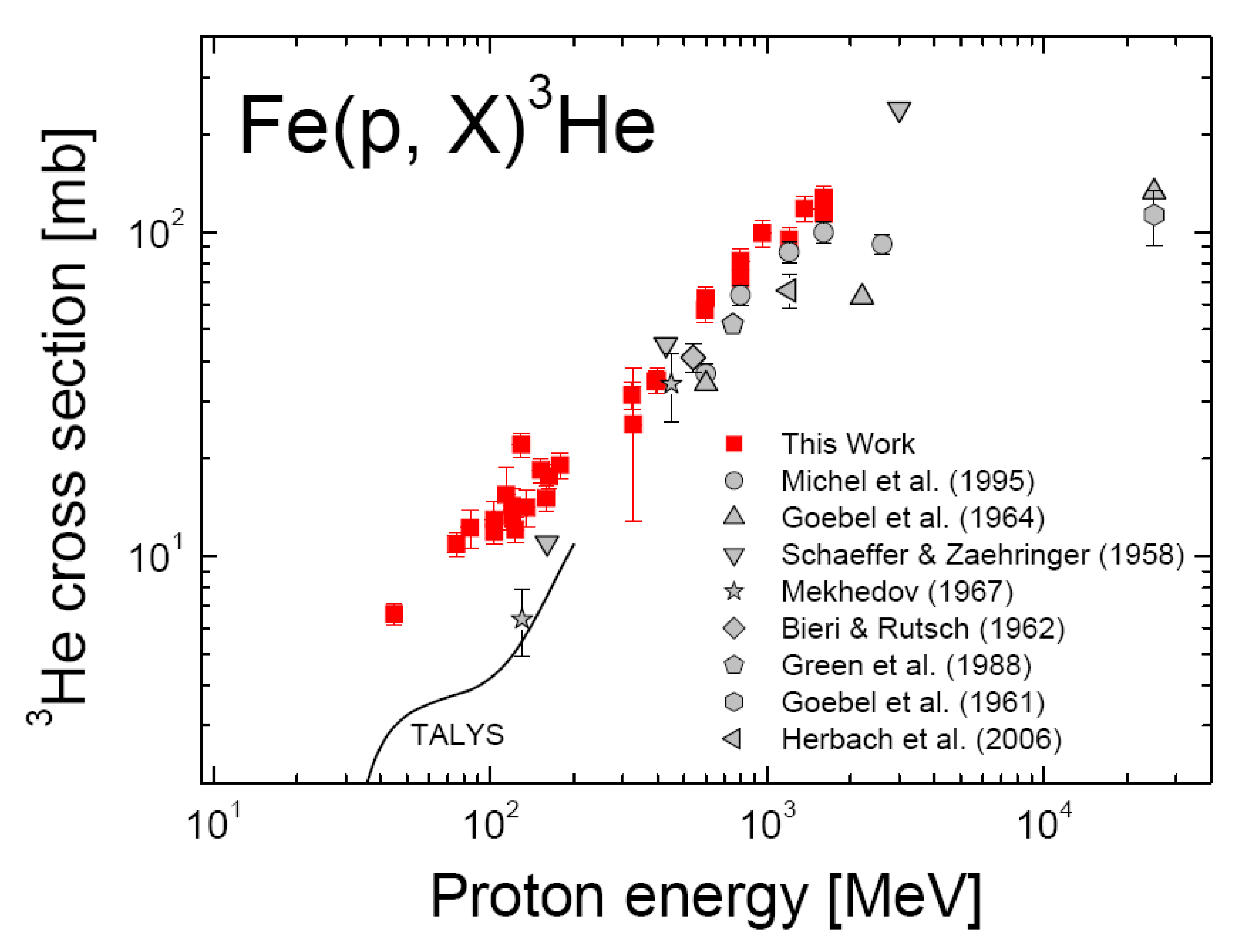


Ammon et al. (2008)



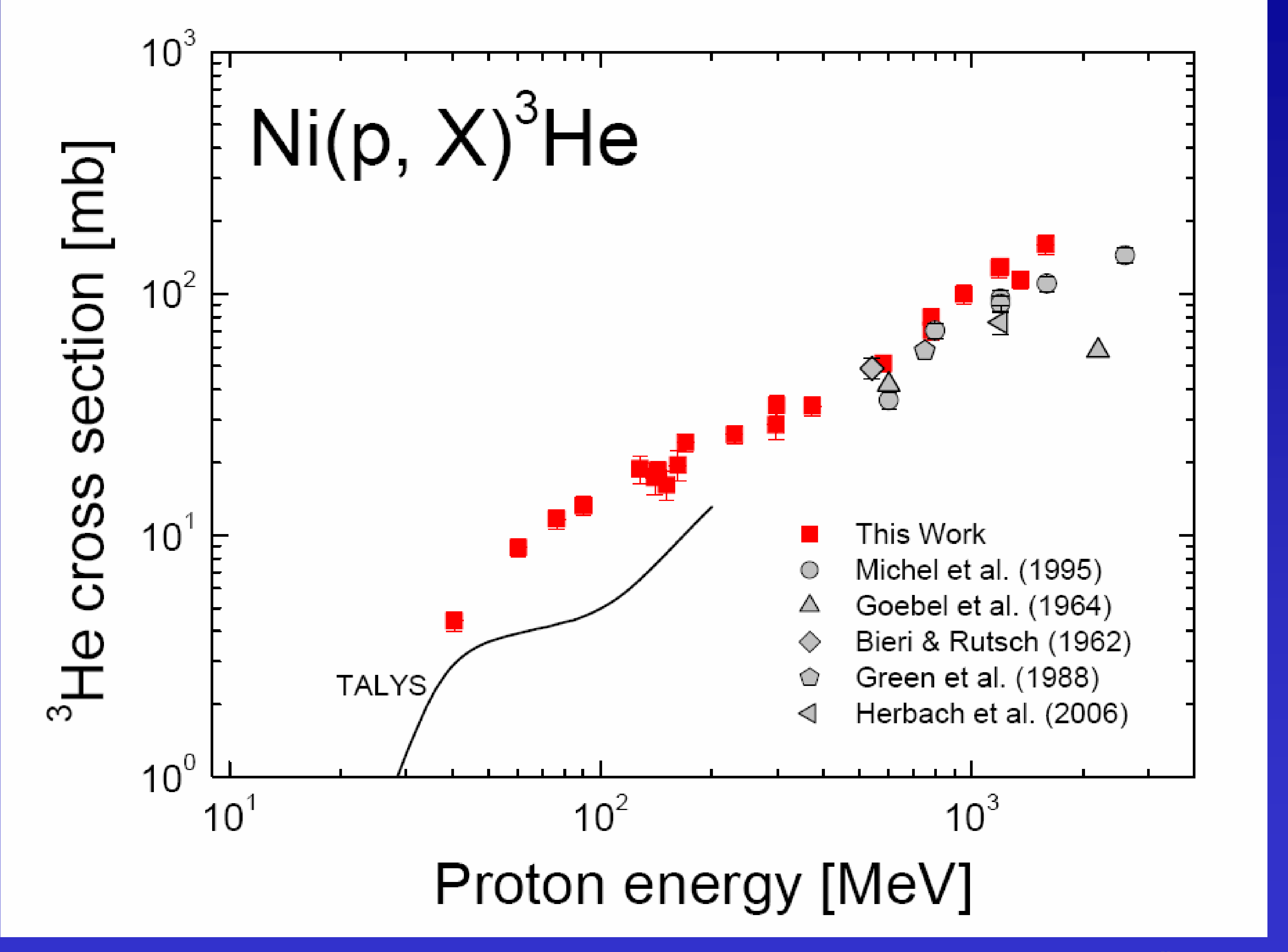
Ammon et al. (2008)

Production of Helium



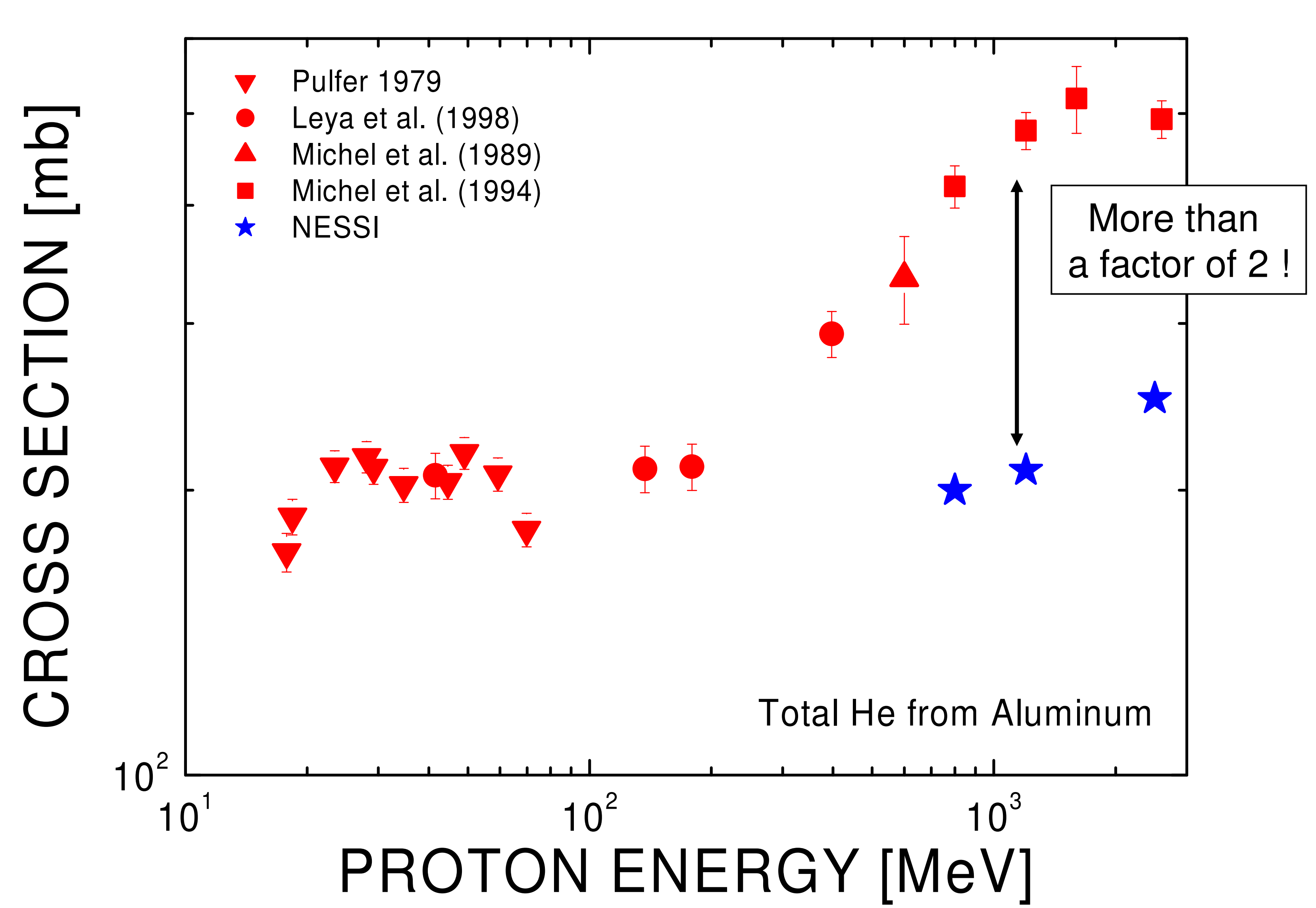
Ammon et al. (2008)

Production of Helium



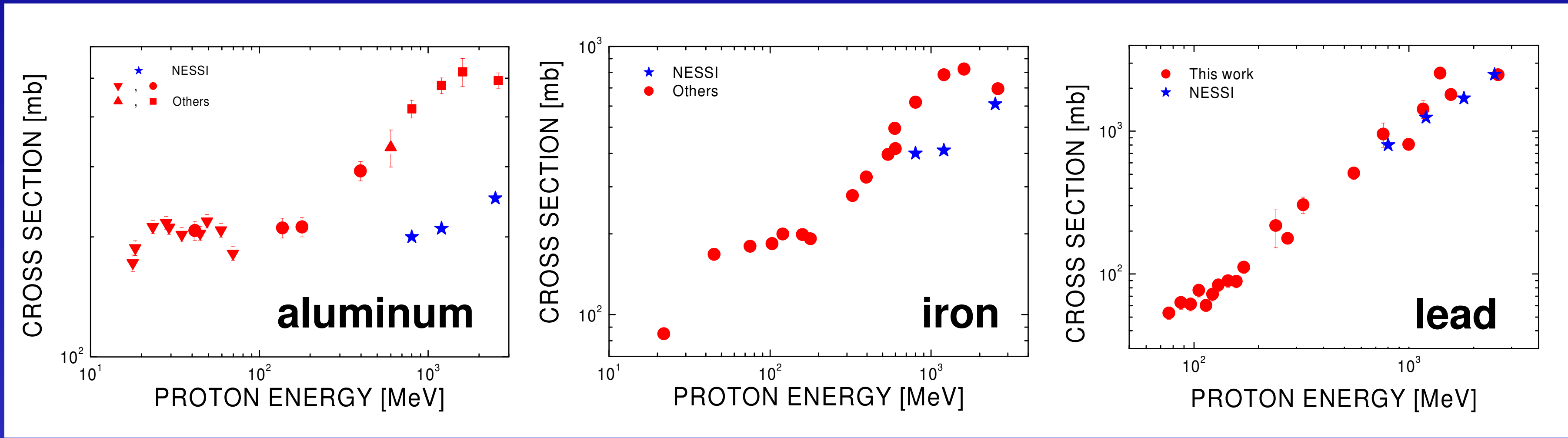
Ammon et al. (2008)

Production of Helium from Aluminum



Leya et al. (2004)

Production of Helium from Al, Fe, and Pb



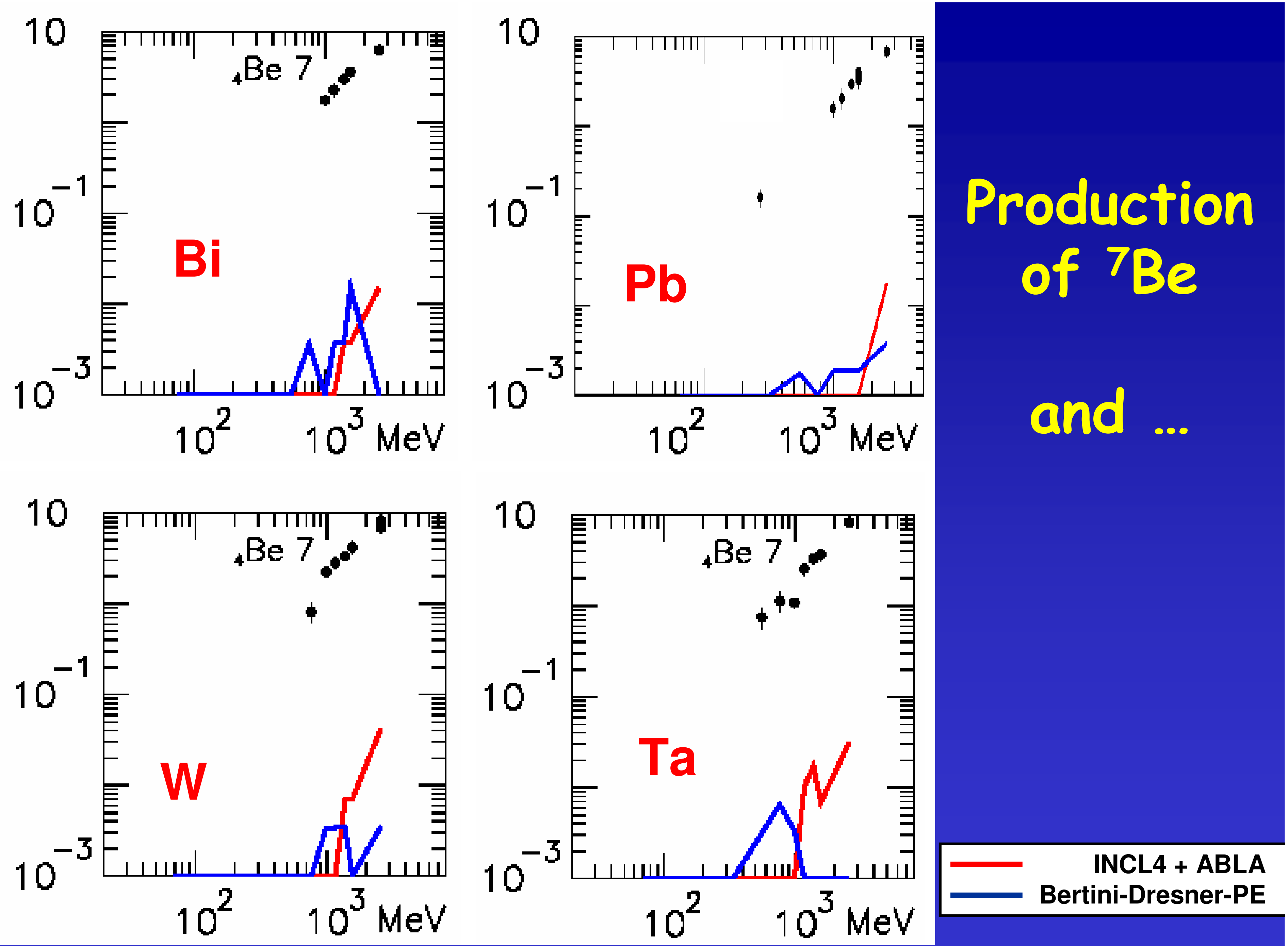
Decreasing evaporation peak

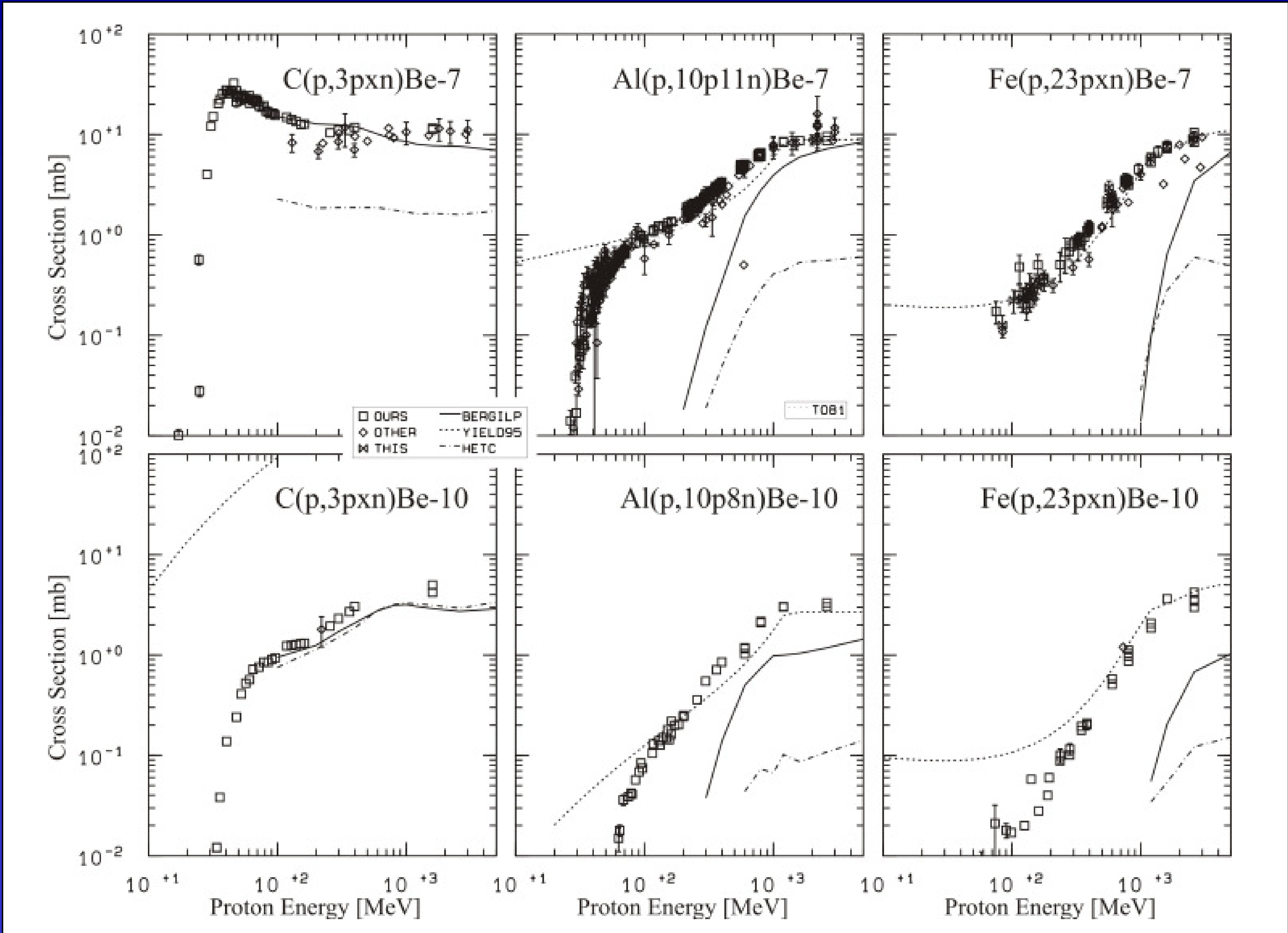
The agreement becomes better with decreasing relevance of the evaporation peak

Leya et al. (2004)

Production of ^{7}Be

and ...





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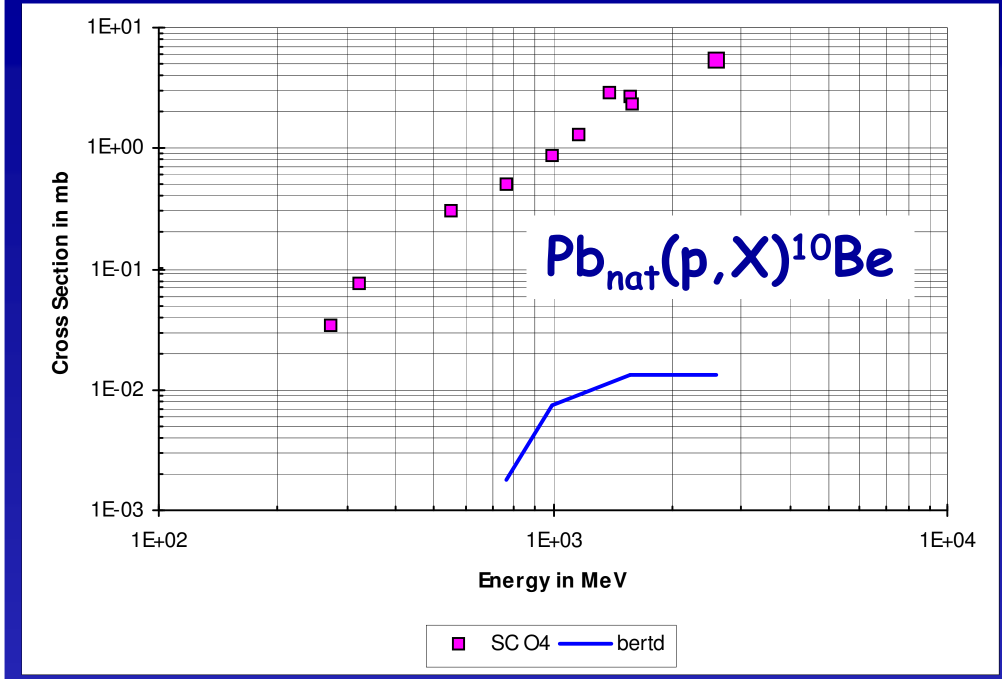

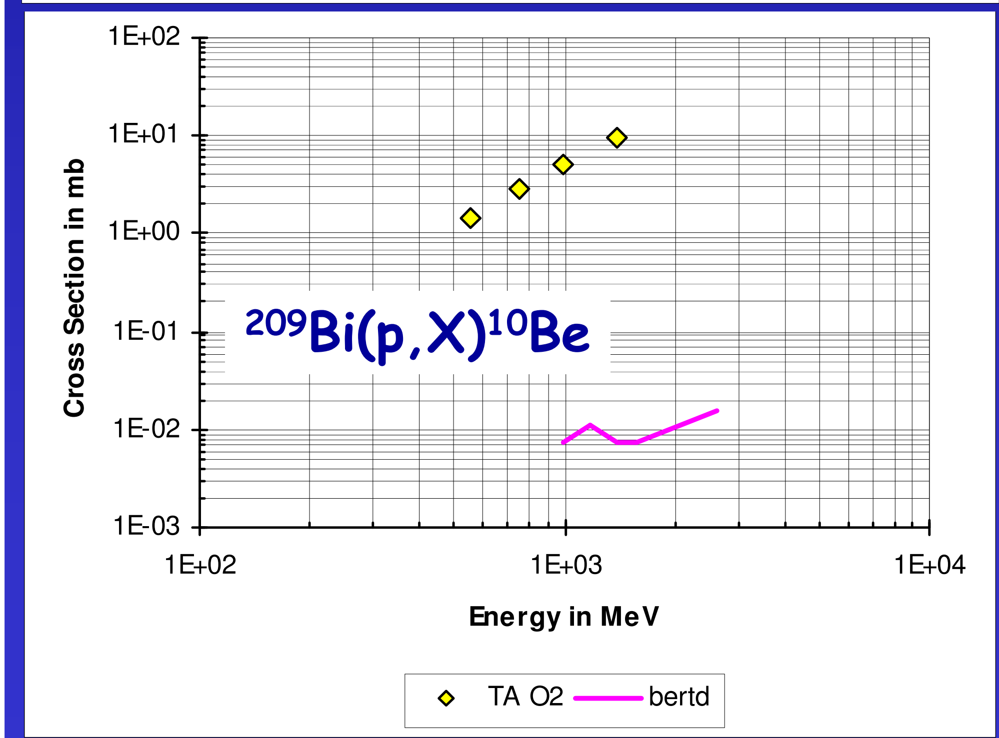

Production of light residual nuclides by fragmentation ?

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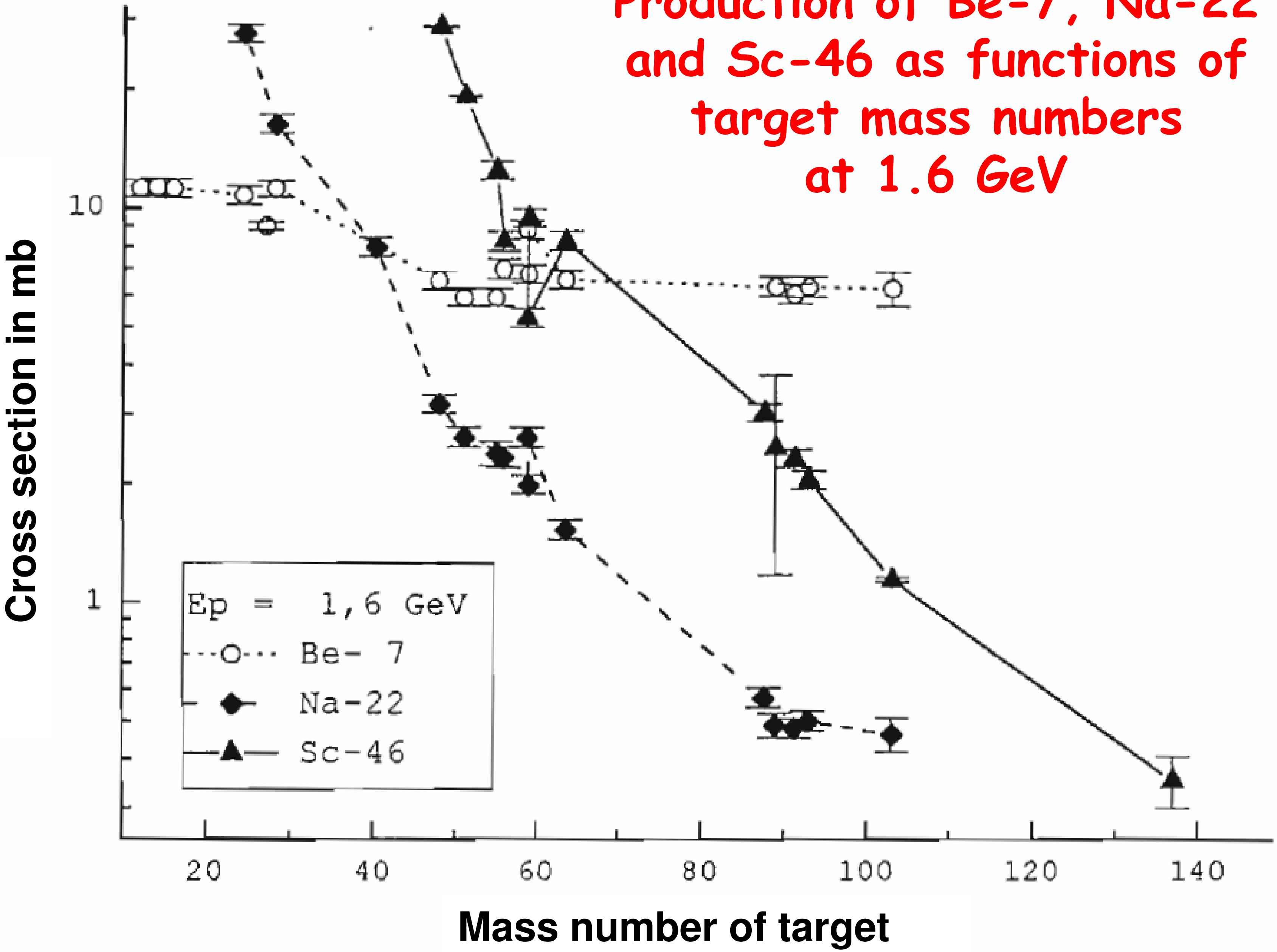
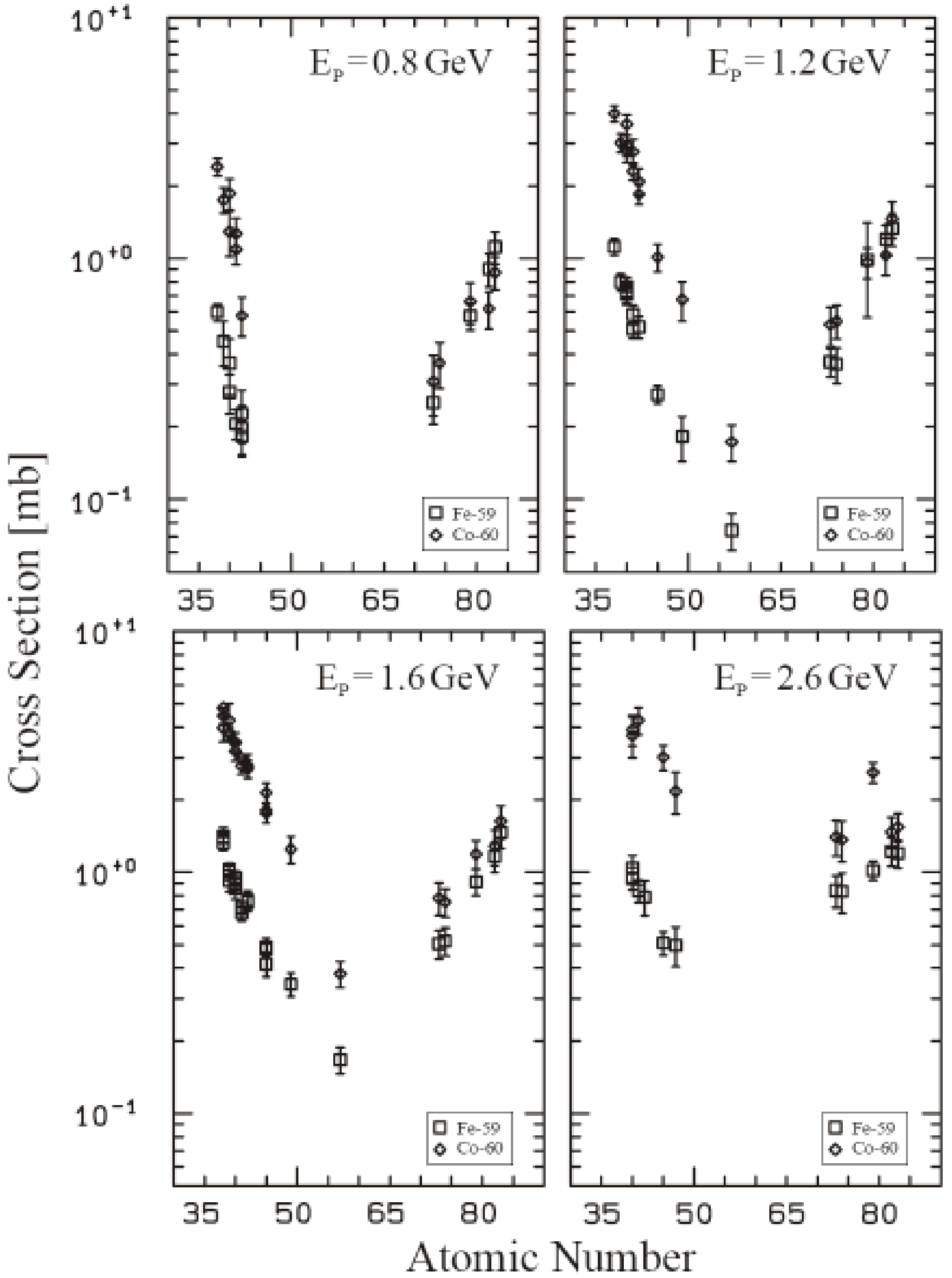
Production of Be-7, Na-22 and Sc-46 as functions of target mass numbers at 1.6 GeV



Leya (1997)



Systematic of the production of Fe-59 and Co-60 as functions of the target element atomic numbers

Product	Targets
H-3	Fe, Ni, Pb
He-3	Al, Mg, Si, Fe, Ni, Pb, Bi
He-3cum	Al, Mg, Si, Fe, Ni, Pb, Bi
He-4	Al, Mg, Si, Fe, Ni, Pb, Bi
Li-6	N
Li-7	N, O
Be-7	C, N, O, F, Mg, Al, Si, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Y, Nb, Mo, Ag, Zr, Ta, W, Au, Pb, Bi
Be-9	N
Be-10	C, N, O, Mg, AL, Si, Ti, Mn, Fe, Co, Ni, Cu, Ta, W, Re, Ir, Pb, B
B-10	N, O
B-11	N,O
C-11	O
C-14	O, Si, Fe, Ni
O-15	O
F-18	Na, Mg, Al, Cu, Ag, Pb
Ne-20	Mg, Al, Si, Fe, Ni, Pb, (Bi)
Ne-21	Mg, Al, Si, Fe, Ni, Pb, (Bi)
Ne-22	Mg, Al, Si, Fe, Ni, Pb, (Bi)
Ne-22cum	Mg, Al, Si, Fe, Ni, Pb, (Bi)
Na-22	Na, Mg, Al, Si, S, K, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Zn, Sr, Y, Zr, Nb, Mo, Rh, Ag, Ta, W, Au, Pb, Bi
Na-24	Mg, Al, Si, Ca, Sc, Ti, V, Mn, Fe, Co, Ni, Cu, Zn, Zr, Nb, Ag, La, Ta, Au, Pb
Al-26	Mg, Al, Si, Ca, Ti, Mn, Fe, Ni, Pb, (Bi)
Mg-28	Si, Ca, Ti, V, Mn, Fe, Co, Ni, Cu, Pb

Systematic of the production of low-mass residues

contribution to NUDATRA WP 5.4 (2007)


SIXTH FRAMEWORK PROGRAMME
EURATOM
Management of Radioactive Waste

Project acronym: EUROTRANS

Project full title: EUROpean Research Programme for the TRANSmutation of High Level Nuclear Waste in an Accelerator Driven System

Contract no.: FI6W-CT-2004-516520

Domain: DM5 NUDATRA

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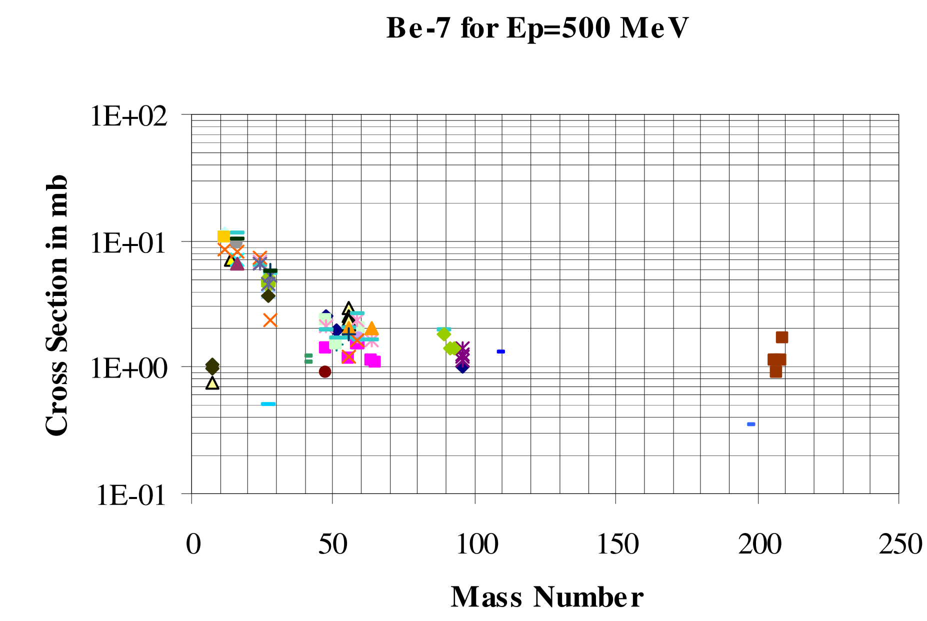
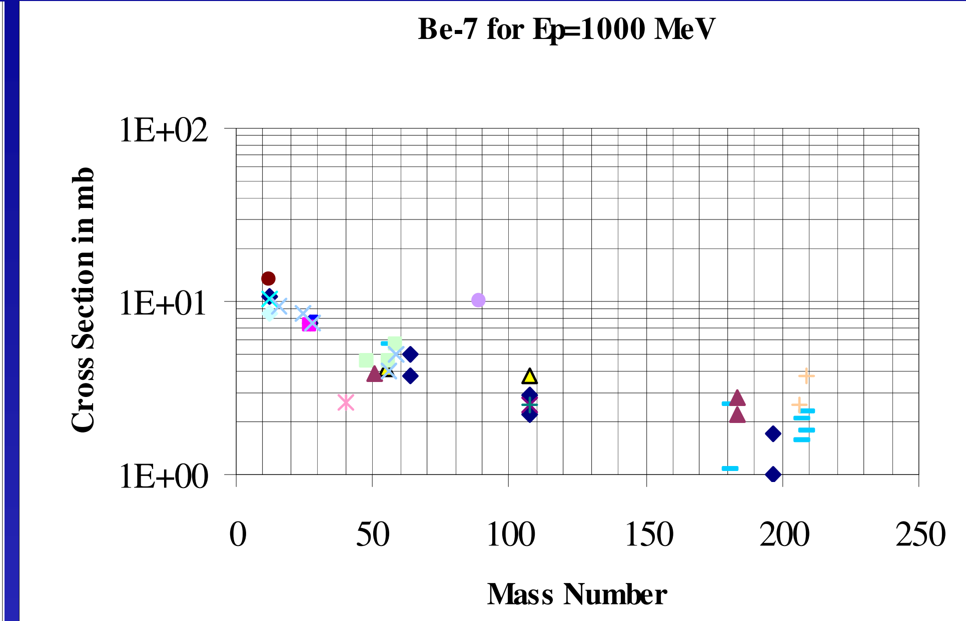
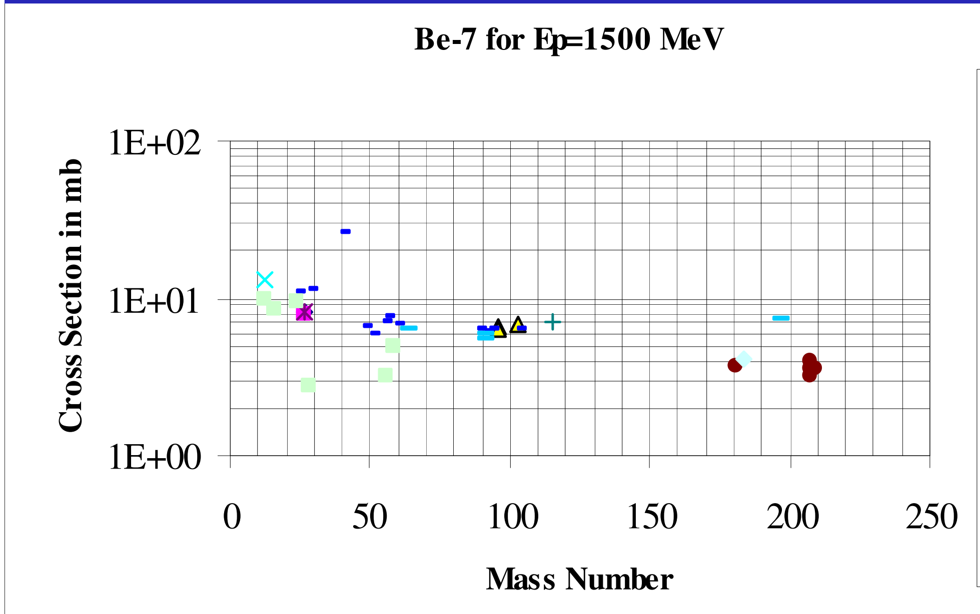
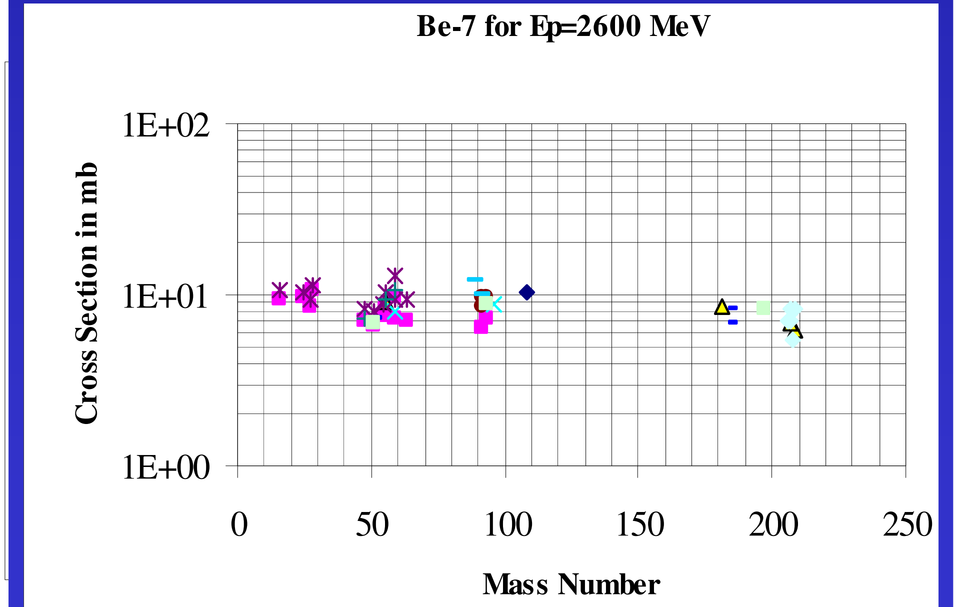
Production of Be-7









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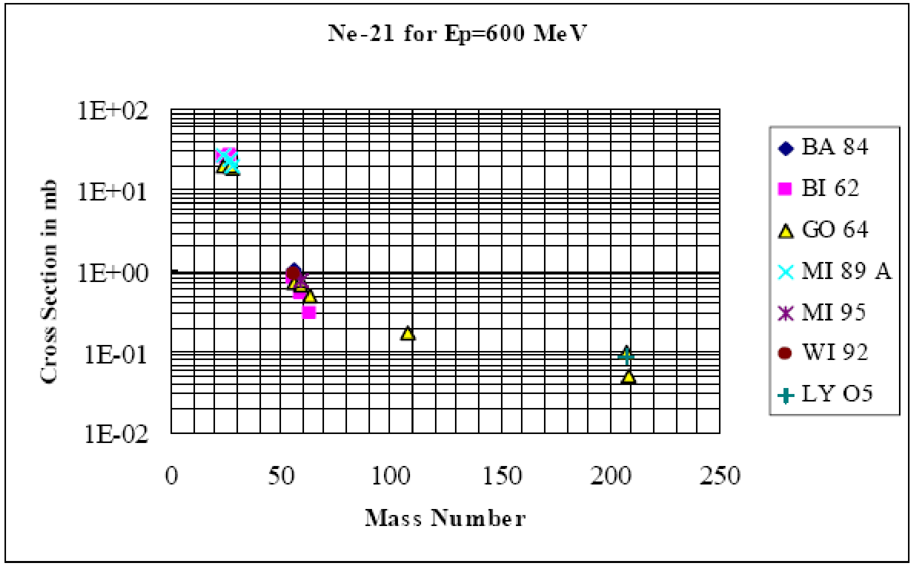
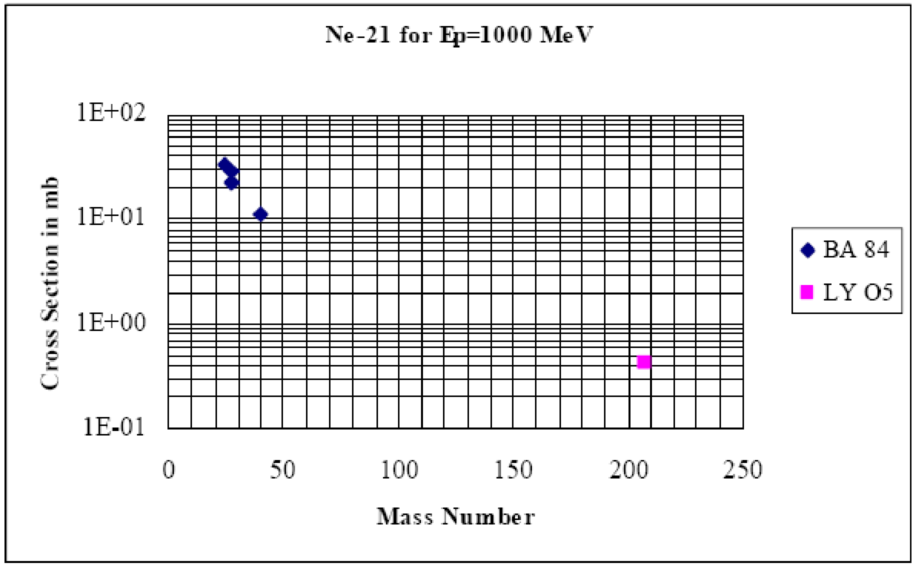
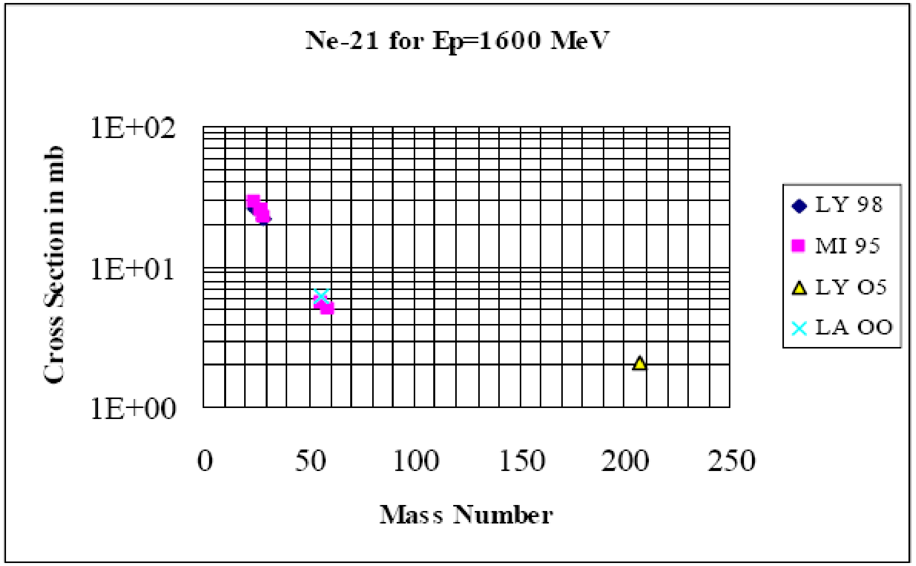
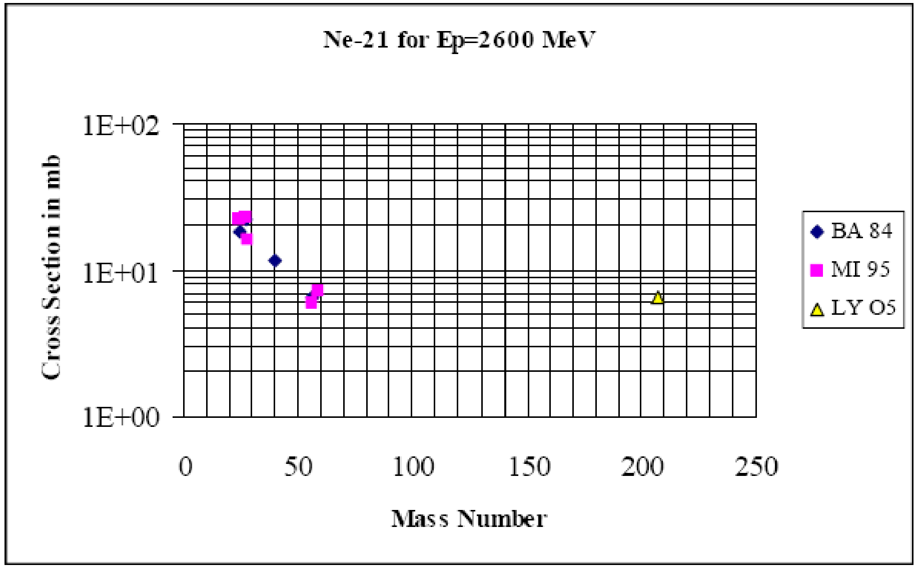
Production of Ne-21

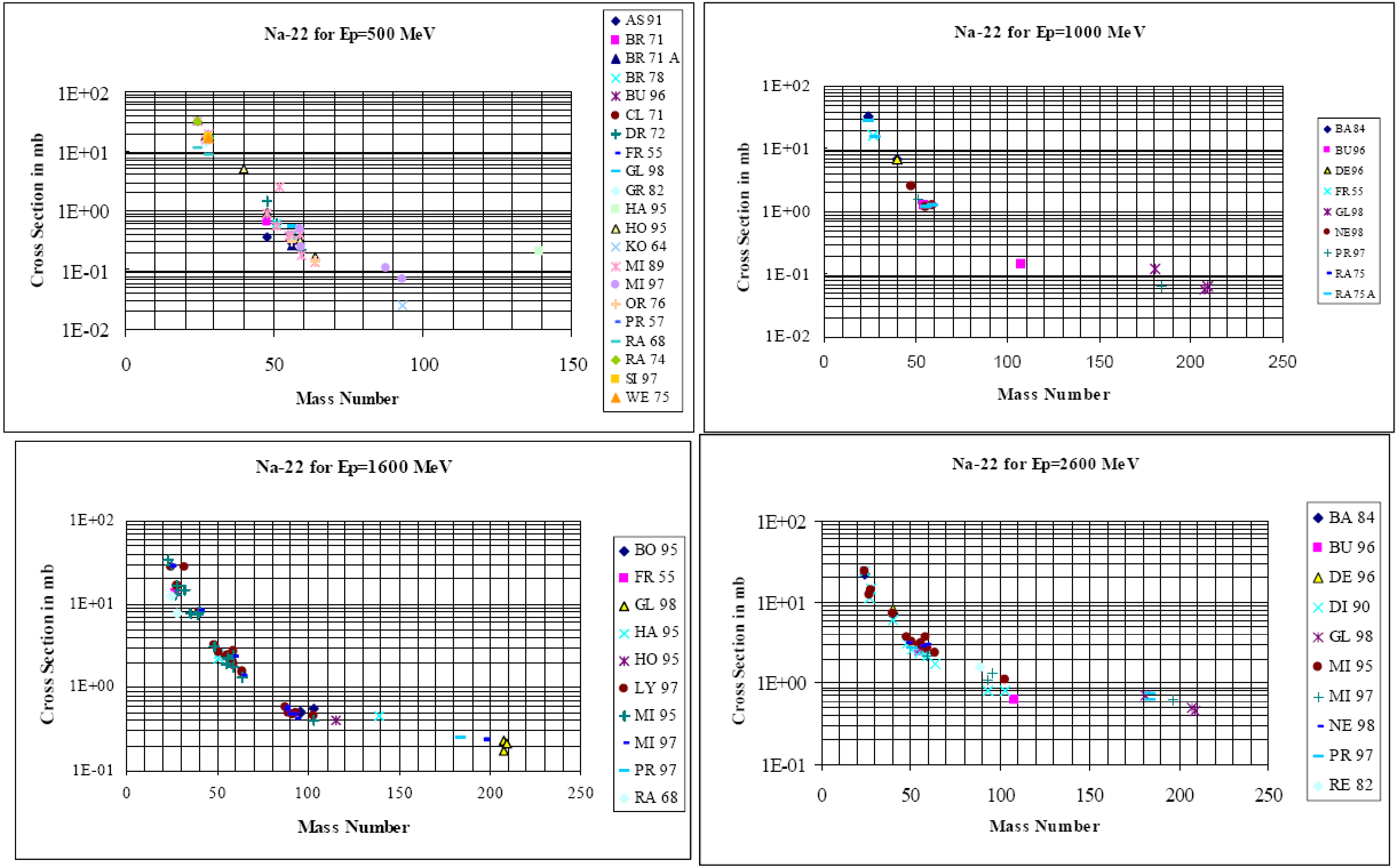








Production of Na-22



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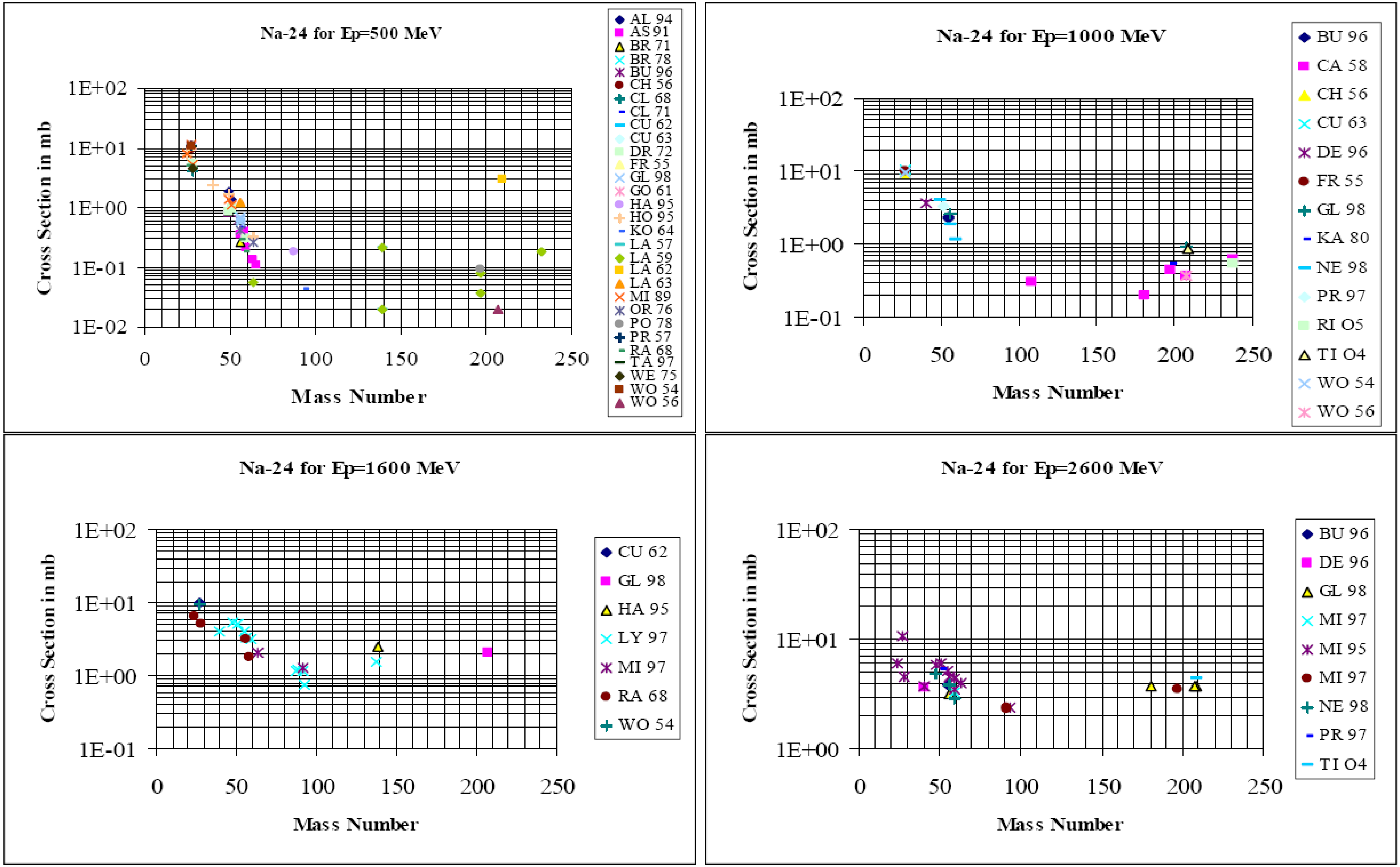
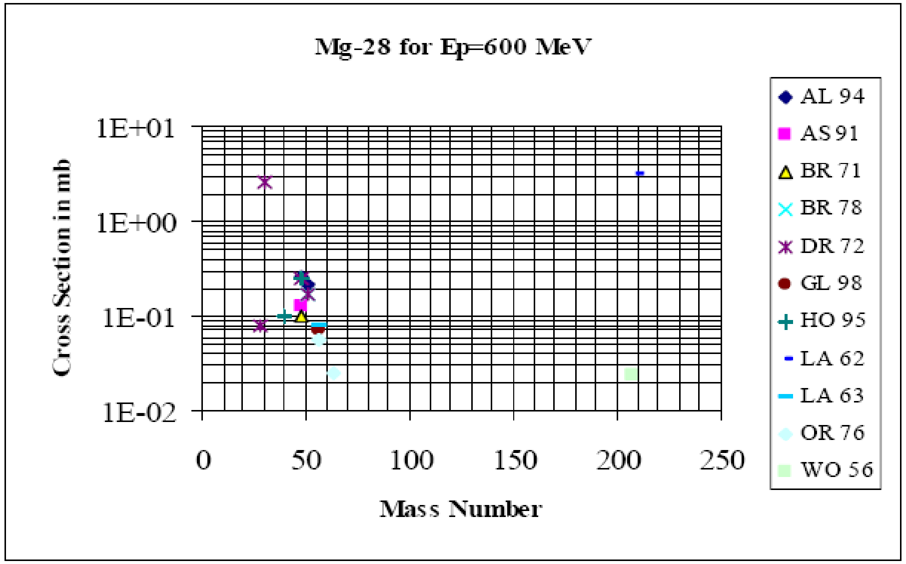
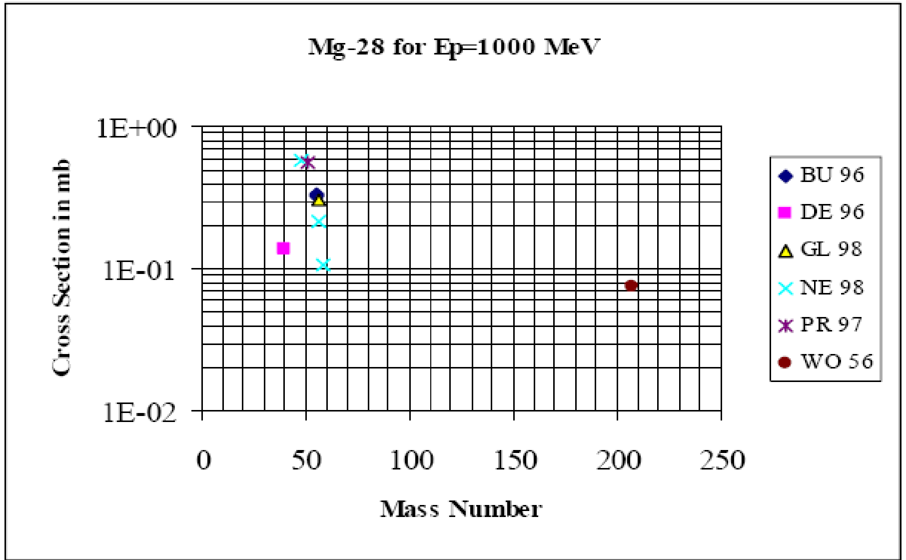
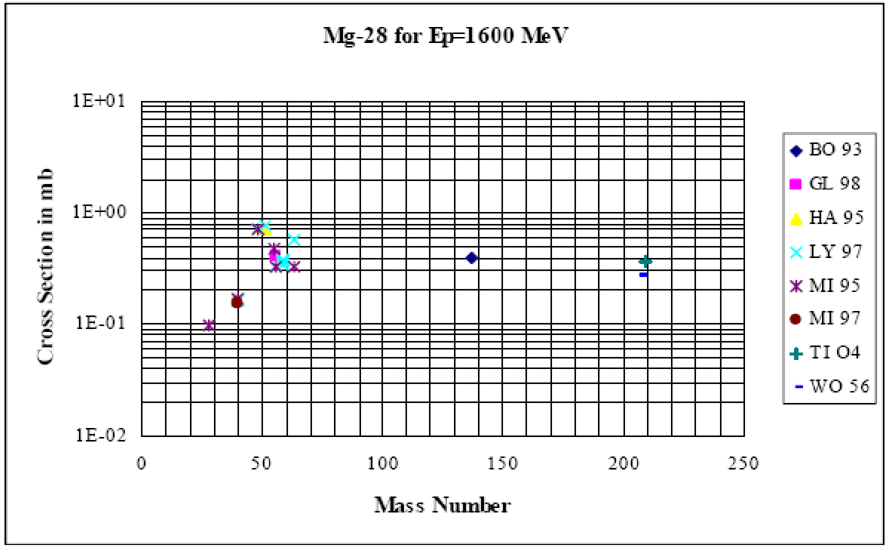
Production of Na-24

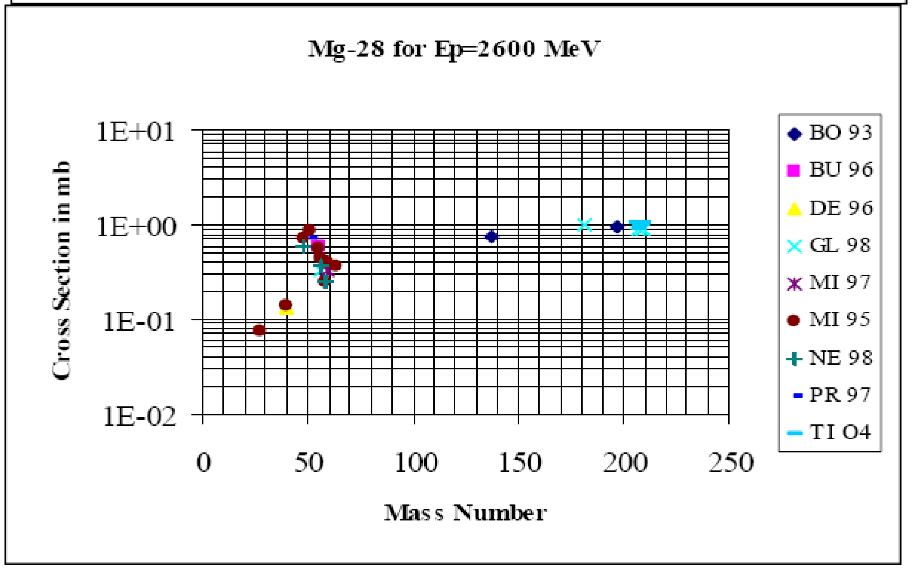


Production of Mg-28

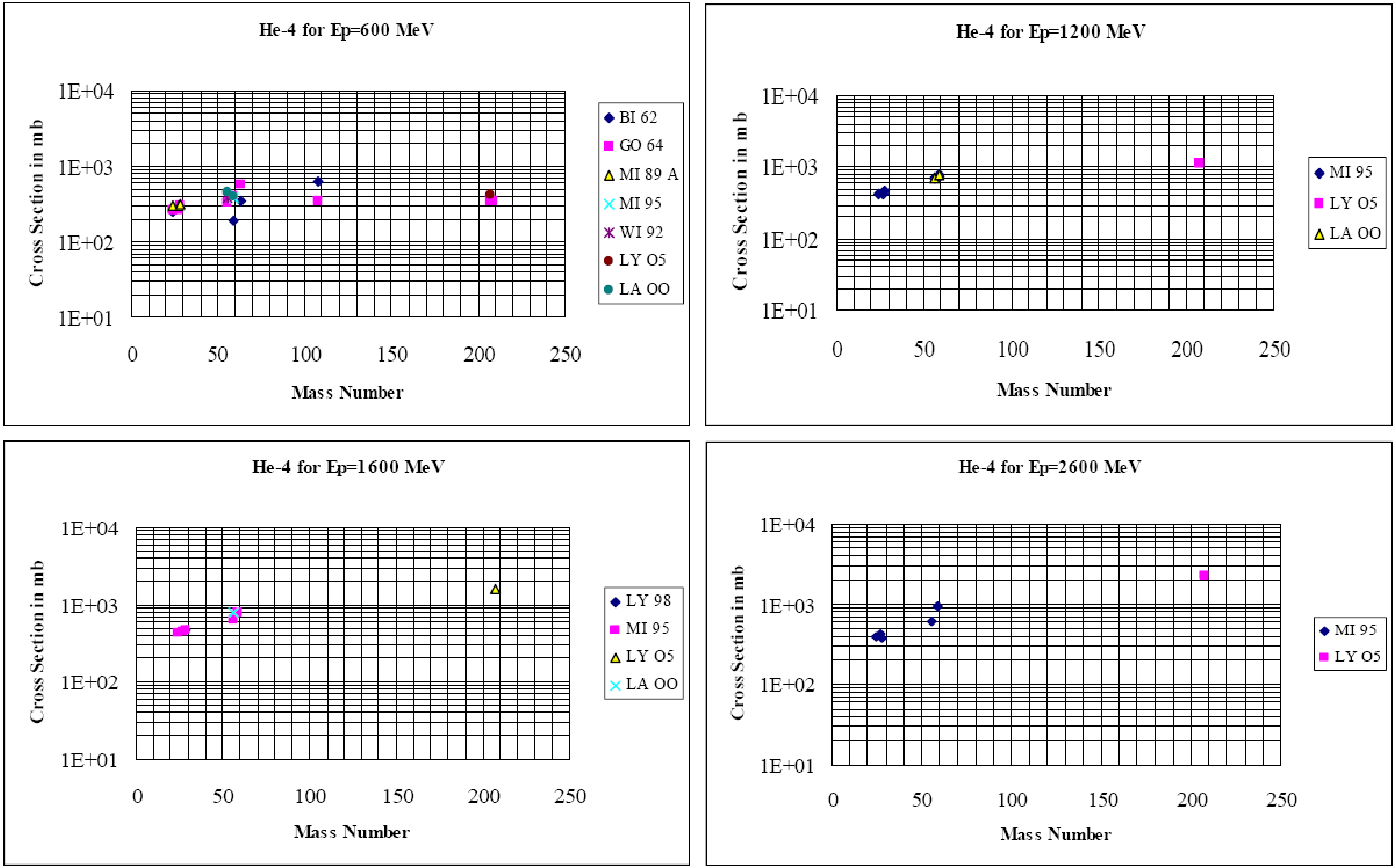








Production of He-4



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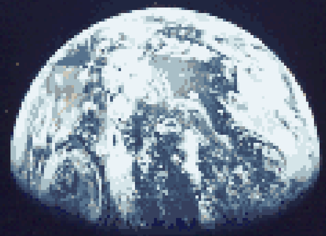

- Relevance of data for the production of residual nuclides at medium energies
- The 1997 NEA intercomparison
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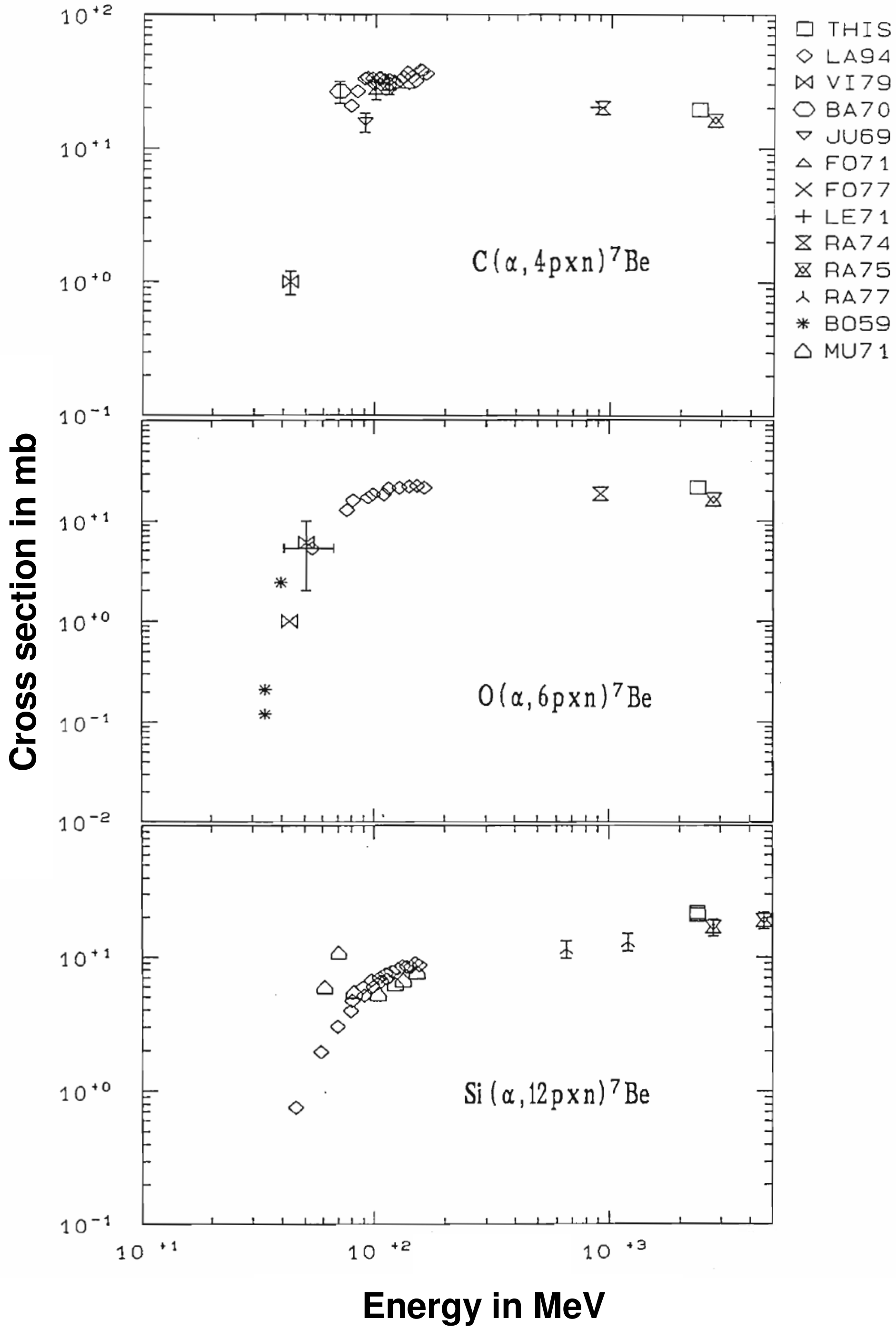
    - proton-induced reactions
    - alpha-induced reactions
    - neutron-induced reactions
  - Thick-target data
- conclusions

Production of Be-7 by ^{4}He-induced reactions



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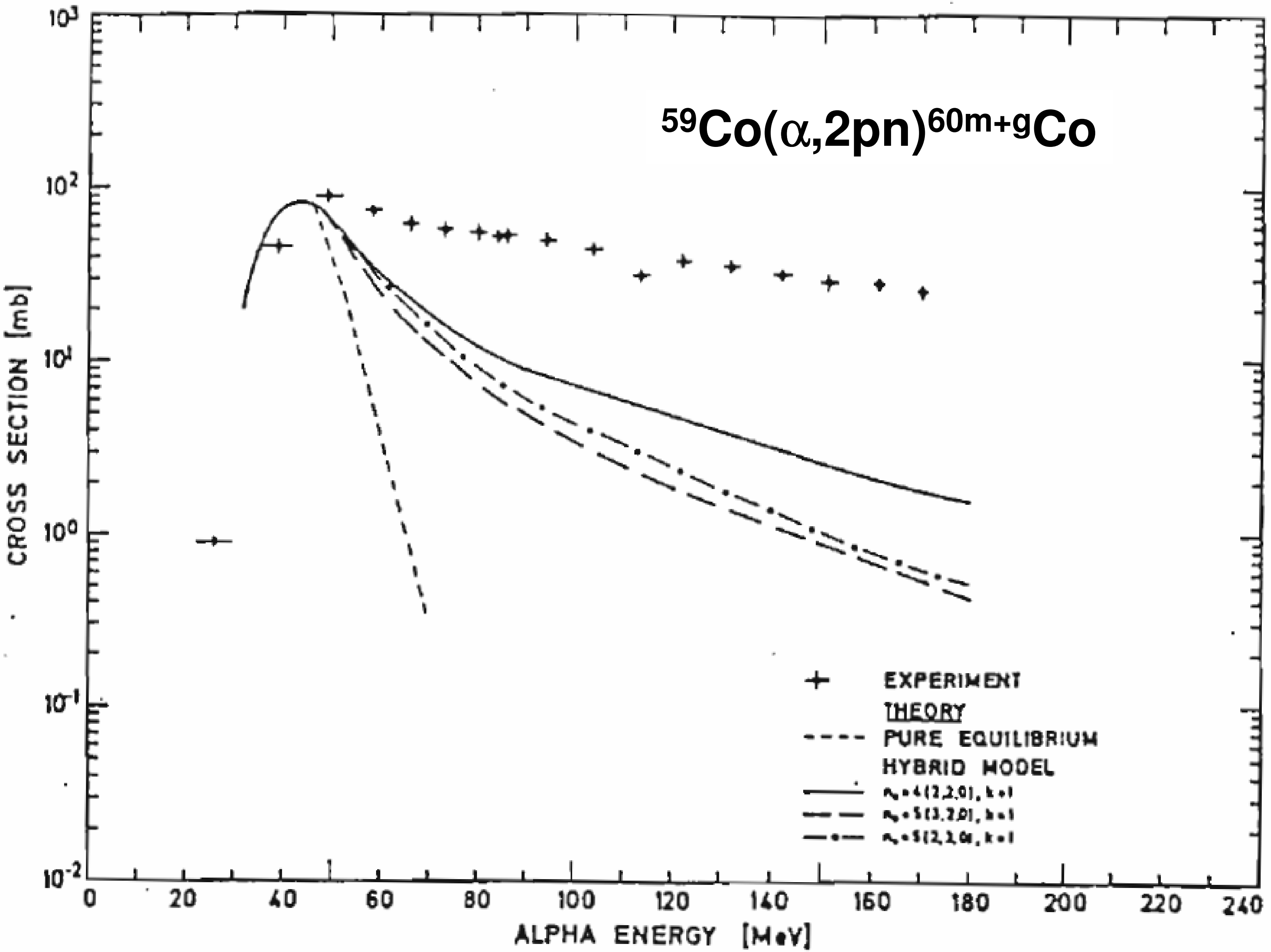
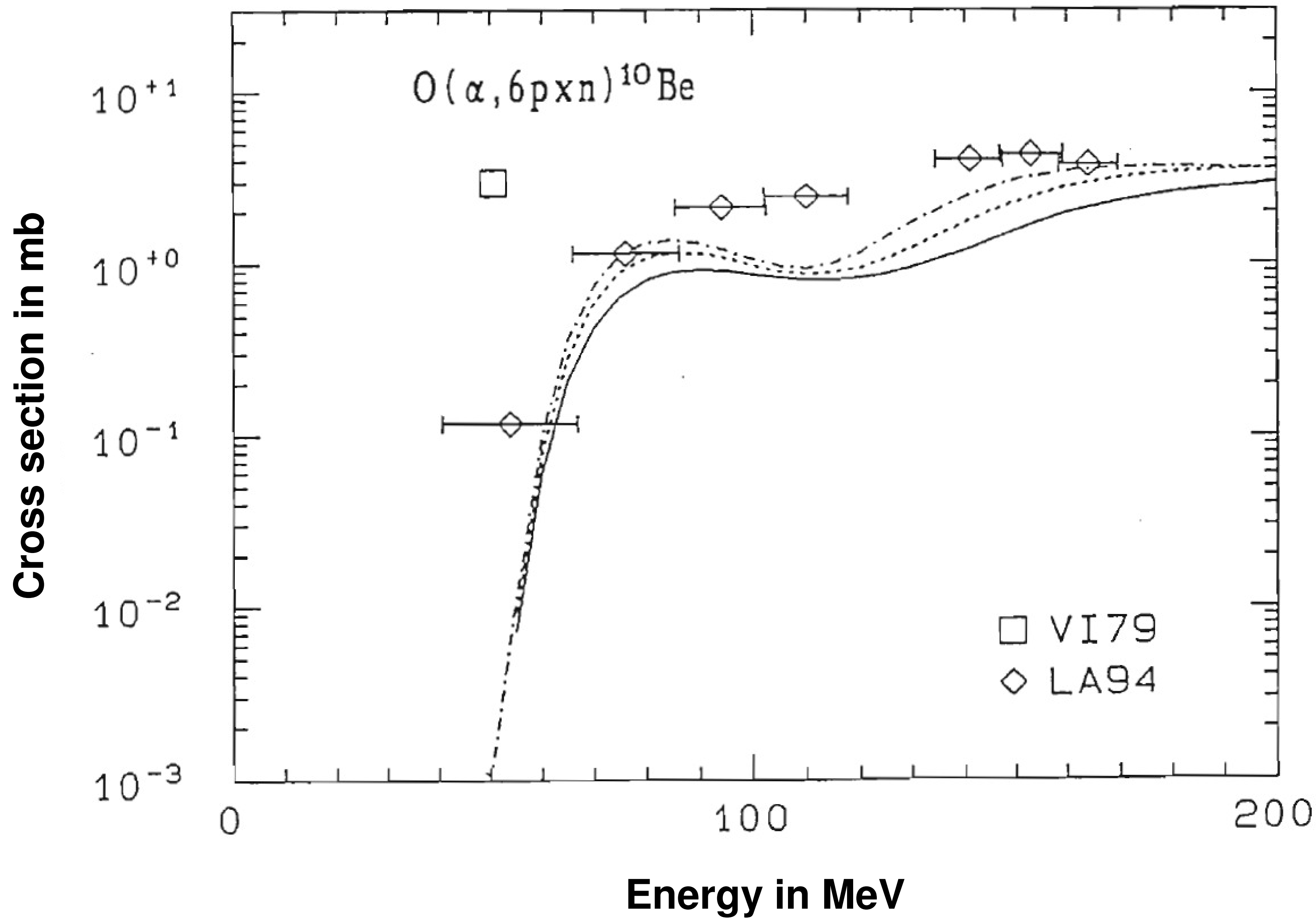
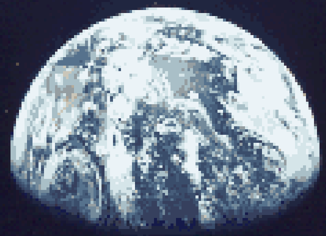


$^{59}Co(\alpha,2pn)^{60m+g}Co$
CROSS SECTION [mb]
ALPHA ENERGY [MeV]
EXPERIMENT
THEORY
PURE EQUILIBRIUM
HYBRID MODEL



O(α,6pxn)^{10}Be
10^{+1}
10^{+0}
10^{-1}
10^{-2}
10^{-3}
0
100
200
VI79
LA94
Cross section in mb
Energy in MeV

Contents



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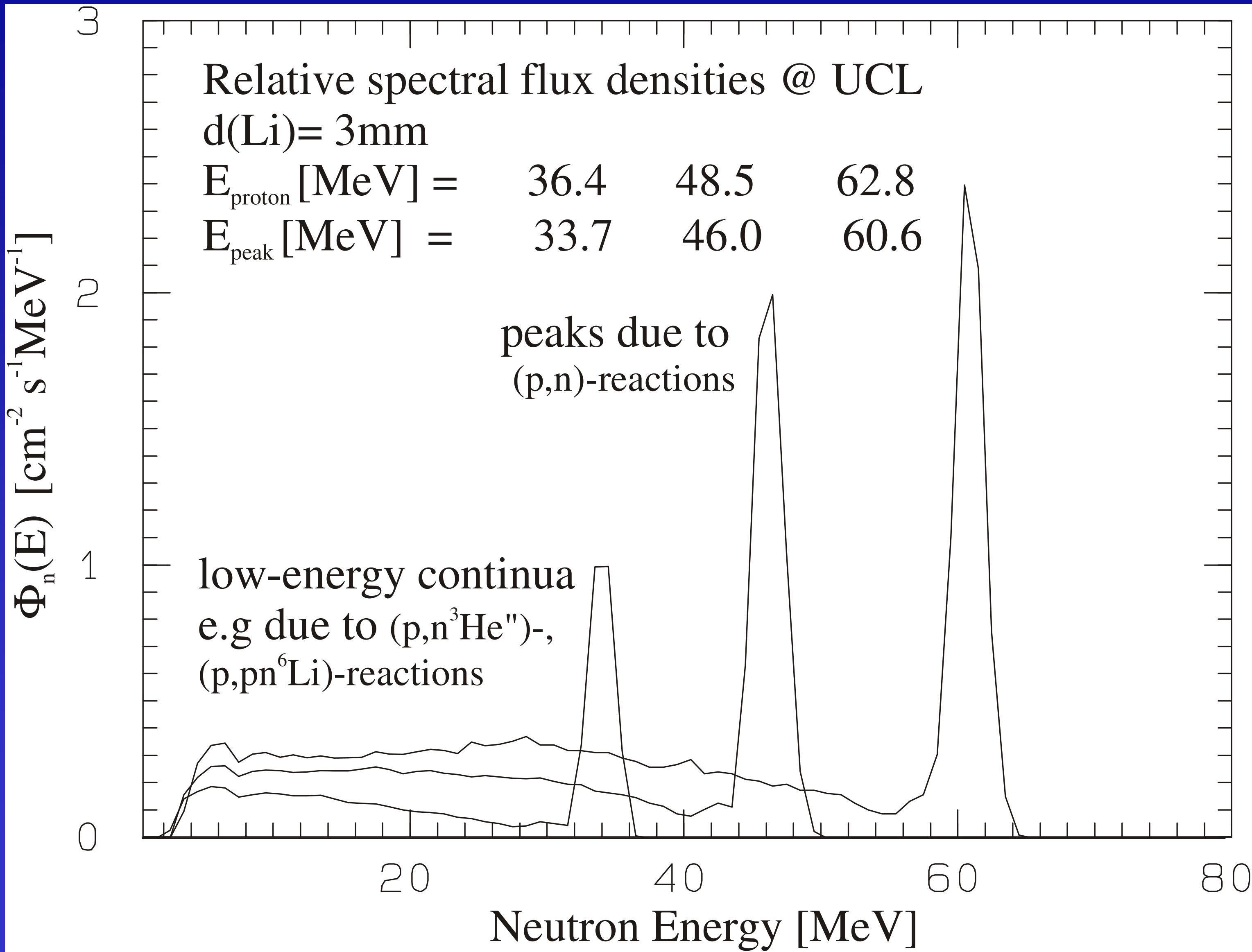
Experiments with Quasi Mono-Energetic Neutrons Produced by the $^7Li(p,n)$-Reaction



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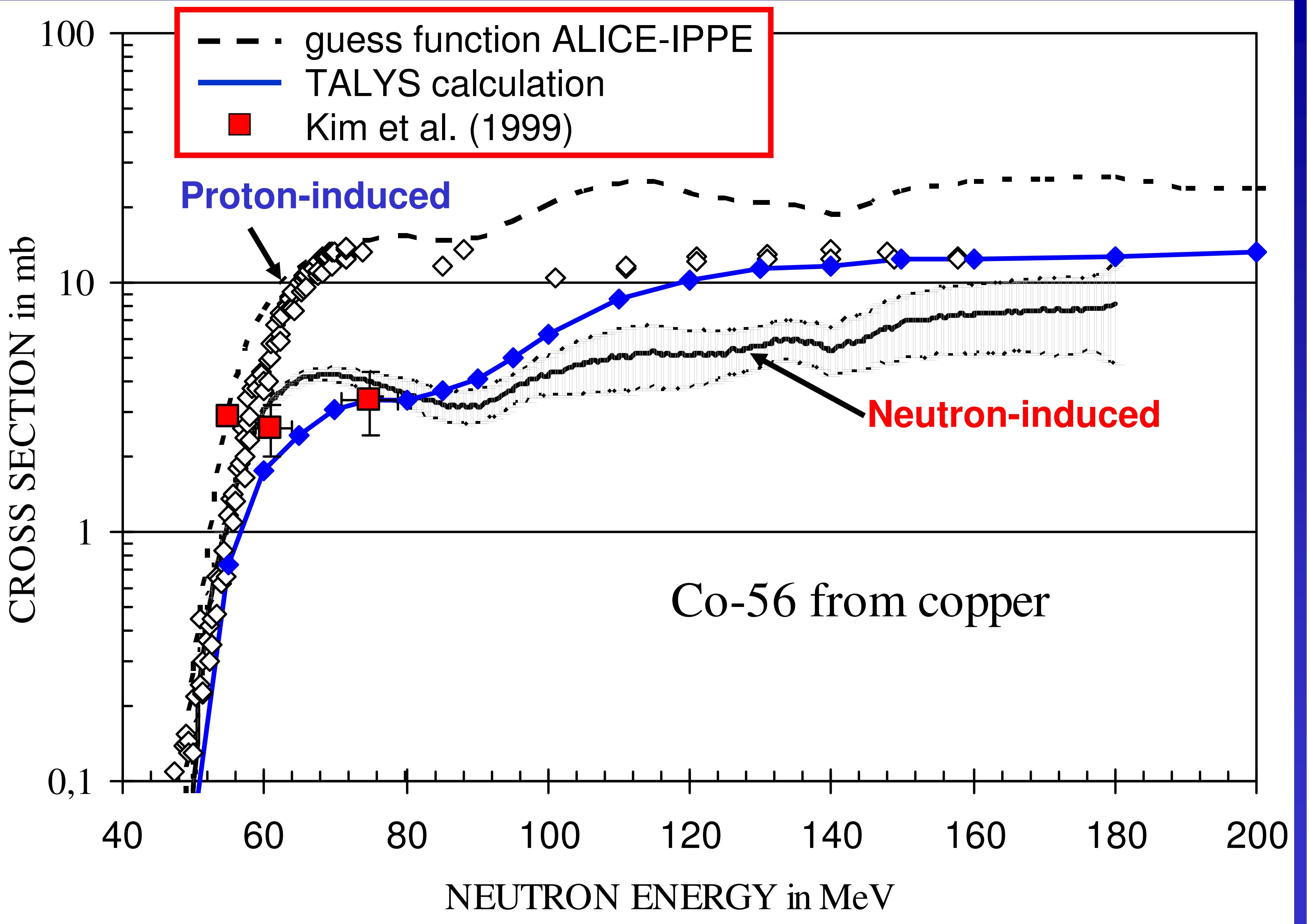

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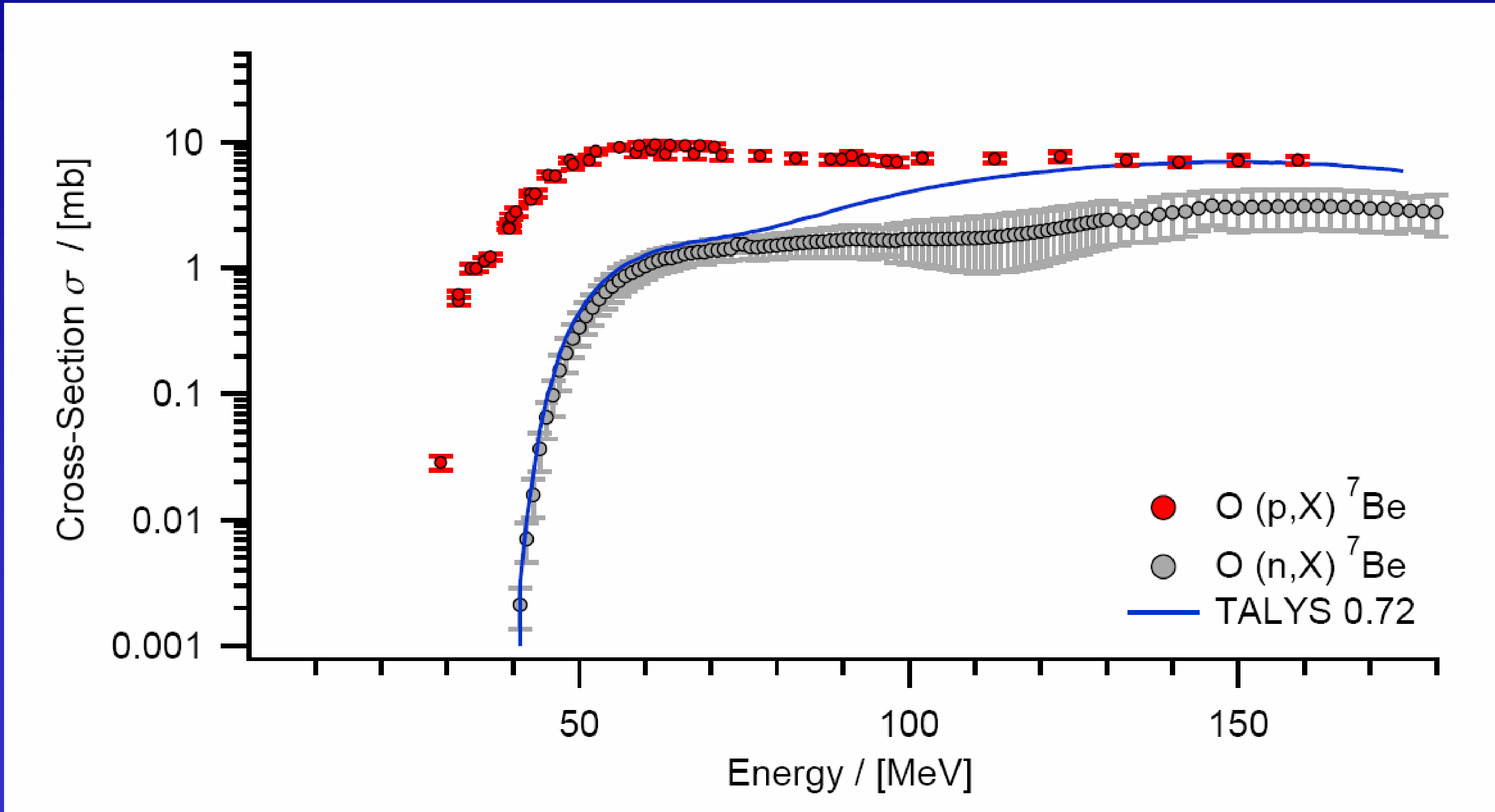
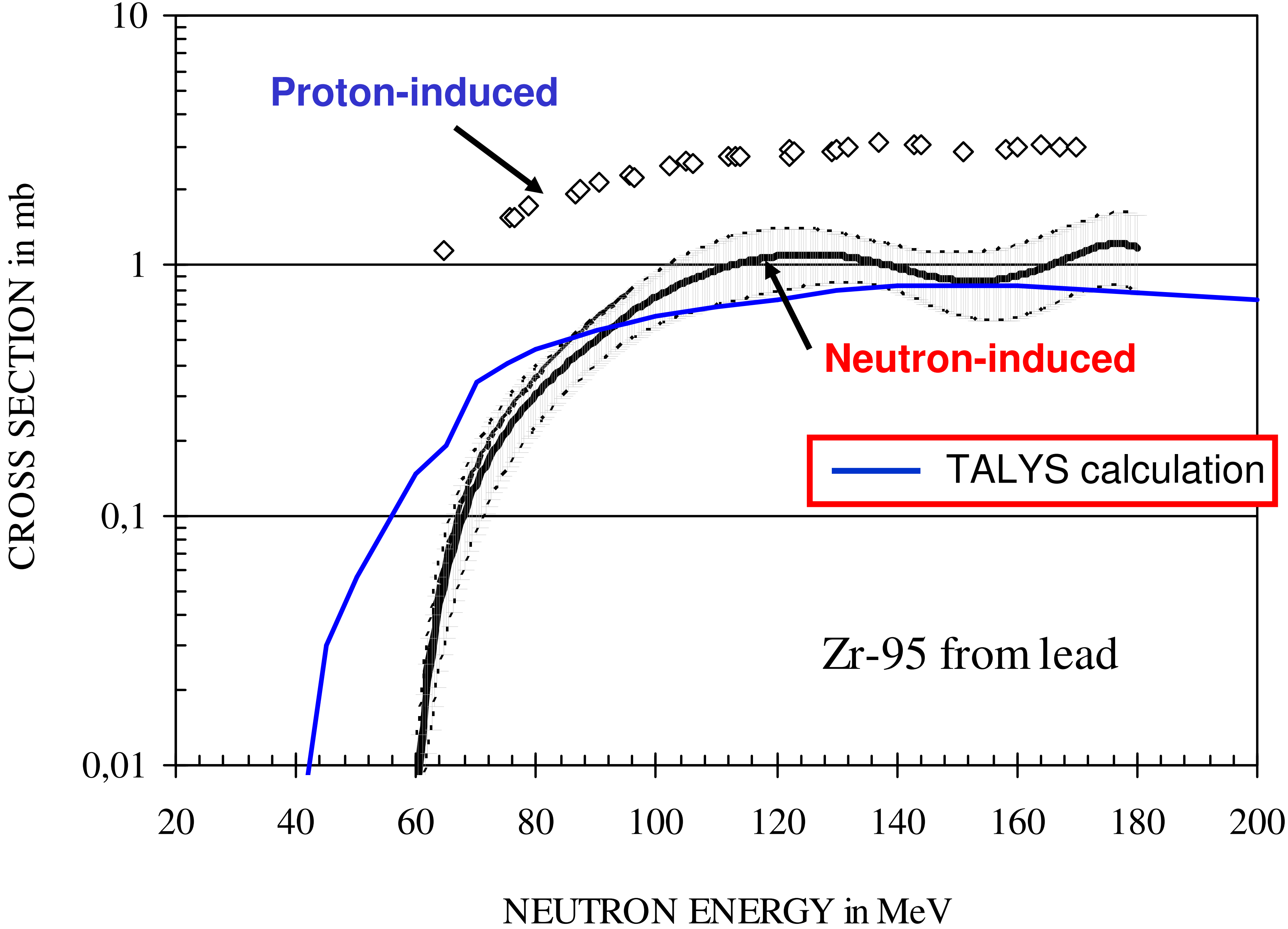
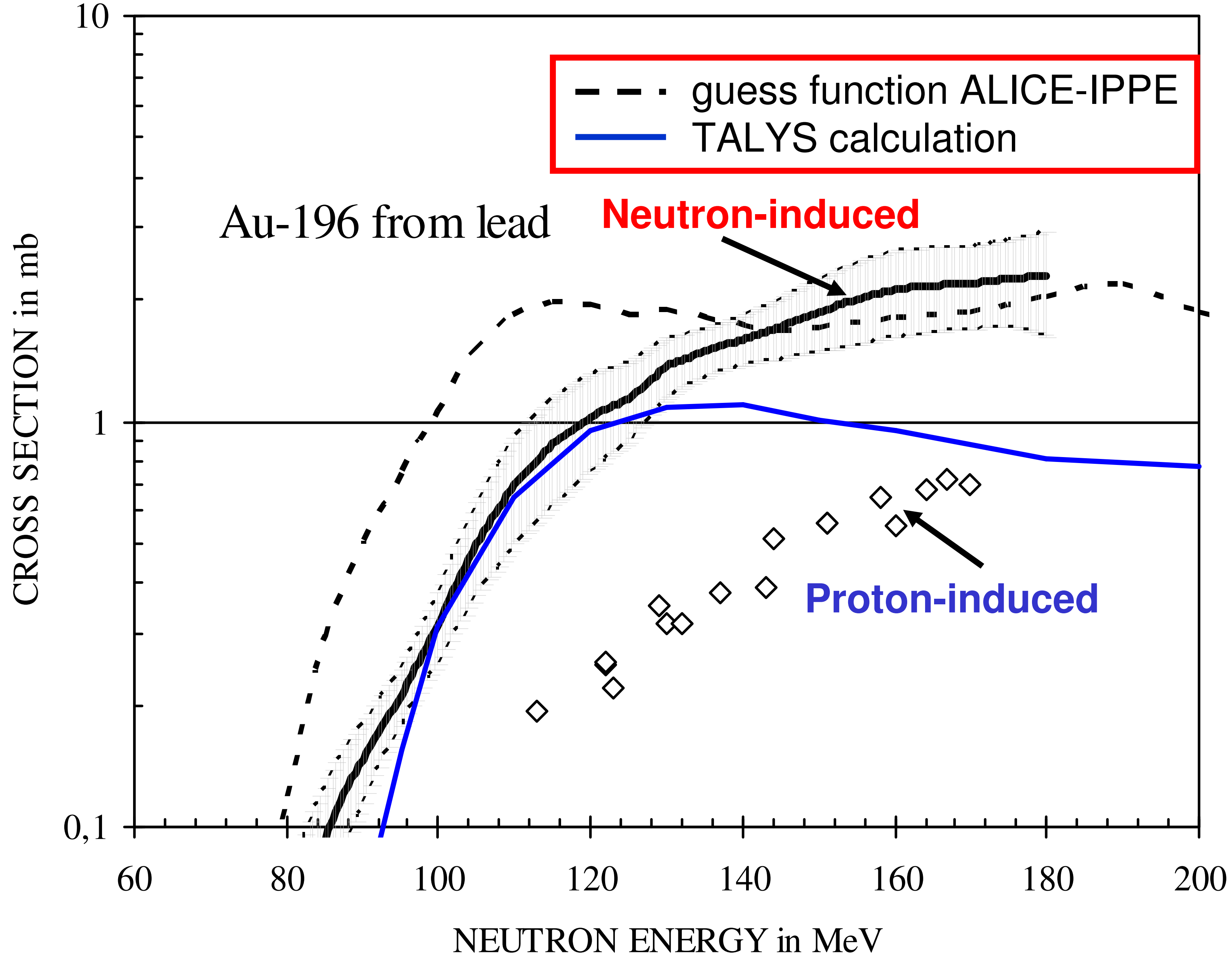
Production of Be-7 from oxygen





Proton-induced
Neutron-induced
TALYS calculation
Zr-95 from lead
CROSS SECTION in mb
NEUTRON ENERGY in MeV
10
1
0,1
0,01
20
40
60
80
100
120
140
160
180
200


guess function ALICE-IPPE
TALYS calculation
Au-196 from lead
Neutron-induced
Proton-induced
10
1
0,1
CROSS SECTION in mb
60
80
100
120
140
160
180
200
NEUTRON ENERGY in MeV

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Thick target data as candidates for testing the performance of models and codes?

- Target matrix Fe
- R = 10 cm
- E_p = 1.6 GeV
- 870 individual targets
- 28 target elements

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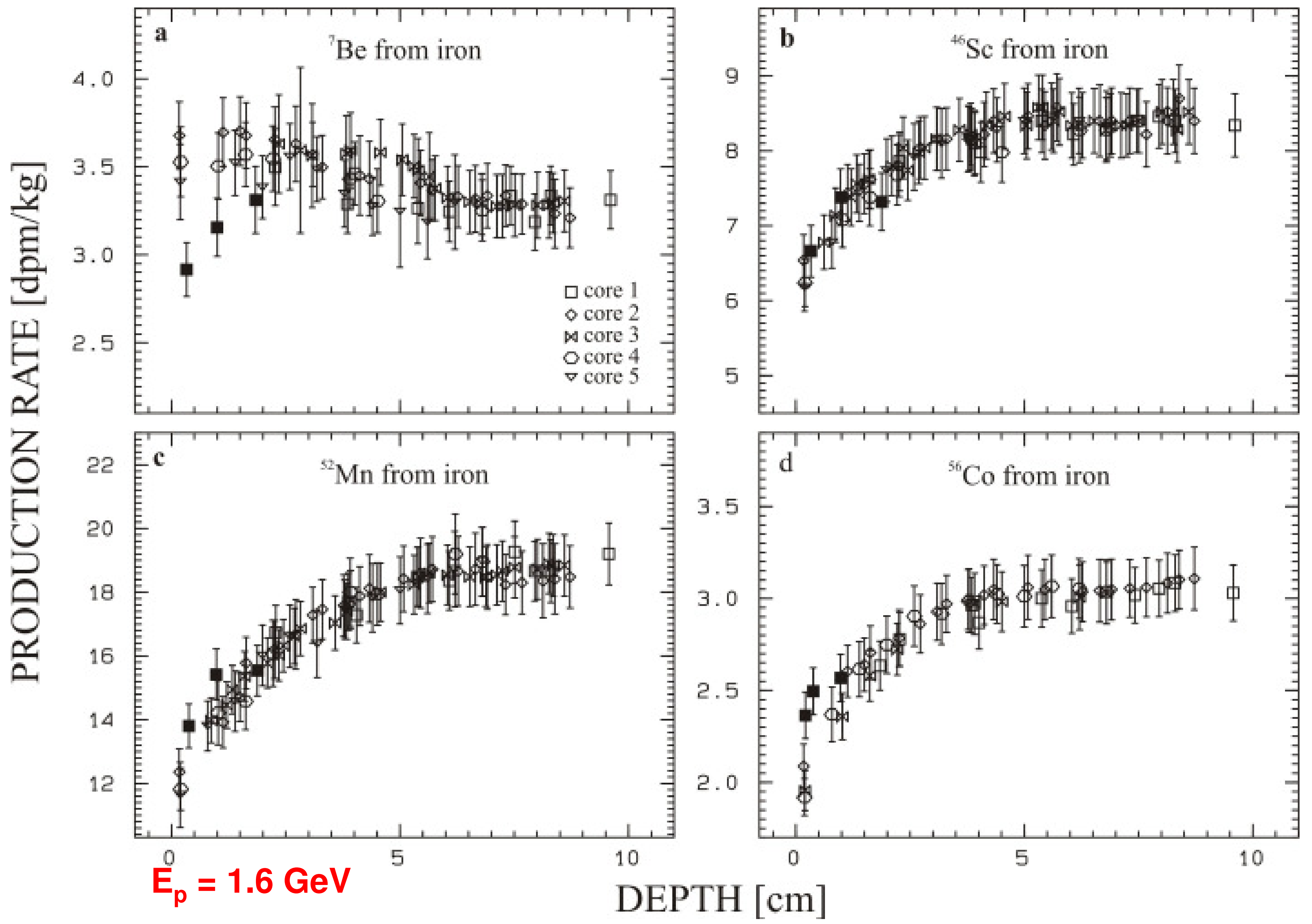

E_p = 1.6 GeV

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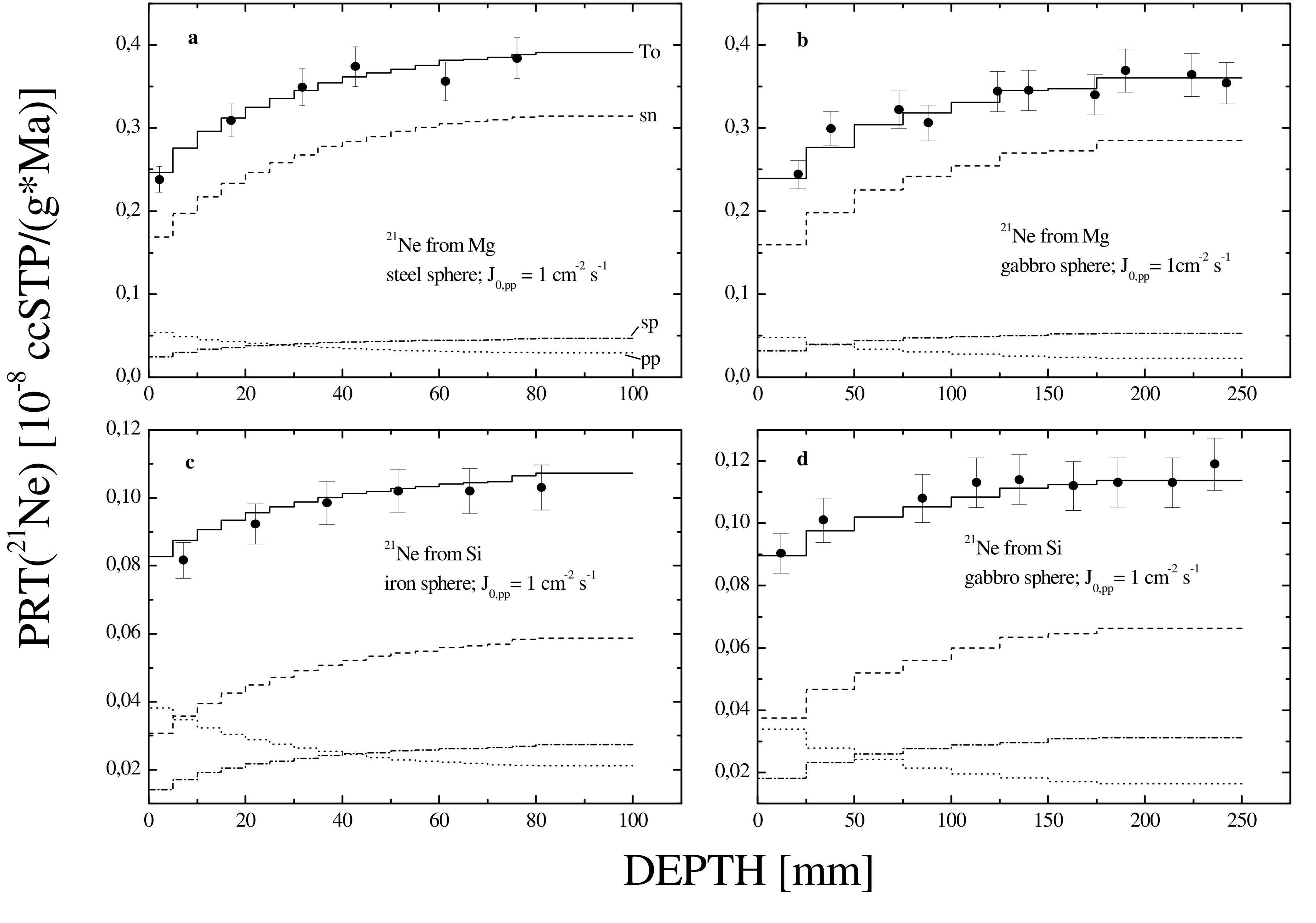
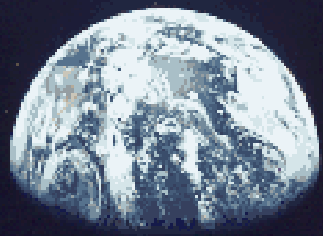
Production of ^{21}Ne in Simulation Experiments



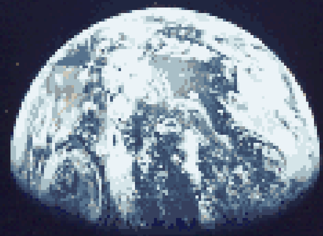
Leya et al. (2002)

Conclusions



- Relevance of data for the production of residual nuclides at medium energies
- The 1997 NEA intercomparison
- Modeling of cosmogenic nuclides in extraterrestrial matter
- Candidate data for testing the performance of model codes on the basis of recent achievements and ongoing work
  - Thin-target data
  - Thick-target data

Conclusions



Candidate data for testing the performance of model codes

- Comprehensive, sytematic and representative coverage of
  - particle types: protons, neutrons, He-4
  - target elements: from C,N,O to U
  - product nuclides: $3 \leq A \leq A_T + 1$
  - energies: 10 – 10,000 MeV

to test the systematic of production cross sections.

- Special reactions for testing extremes of nuclear reactions:
  - unbalanced nucleons in the exit channel,
  - competition between spallation and fission,
  - competition between evaporation, PE decay, and fission,
  - (multi-)fragmentation

for testing extremes of nuclear reactions.


The End