Measuring Neutron Separation Energies Far from Stability

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Introduction

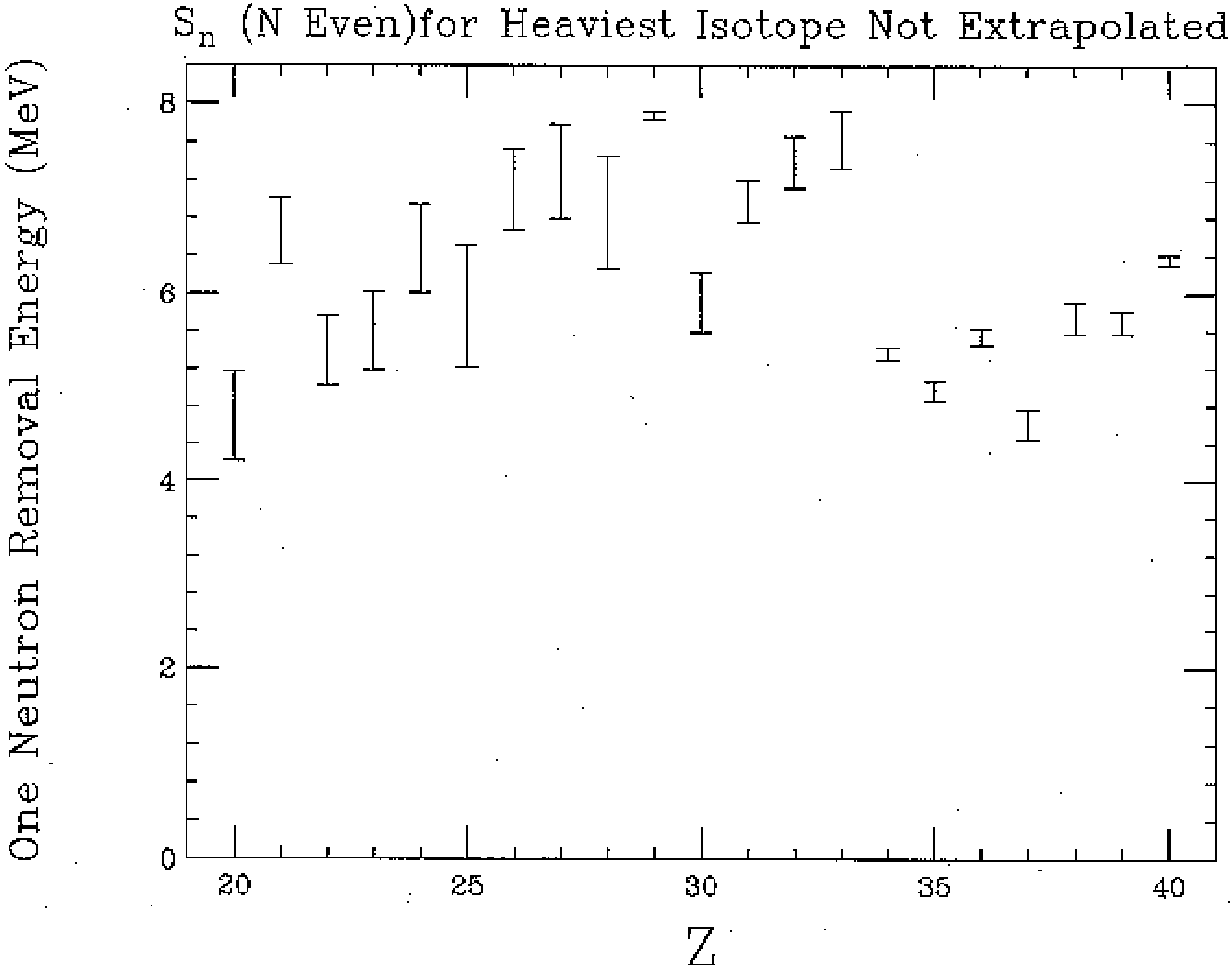
- Asymmetry energy drives neutron separation energy to zero at the drip line.

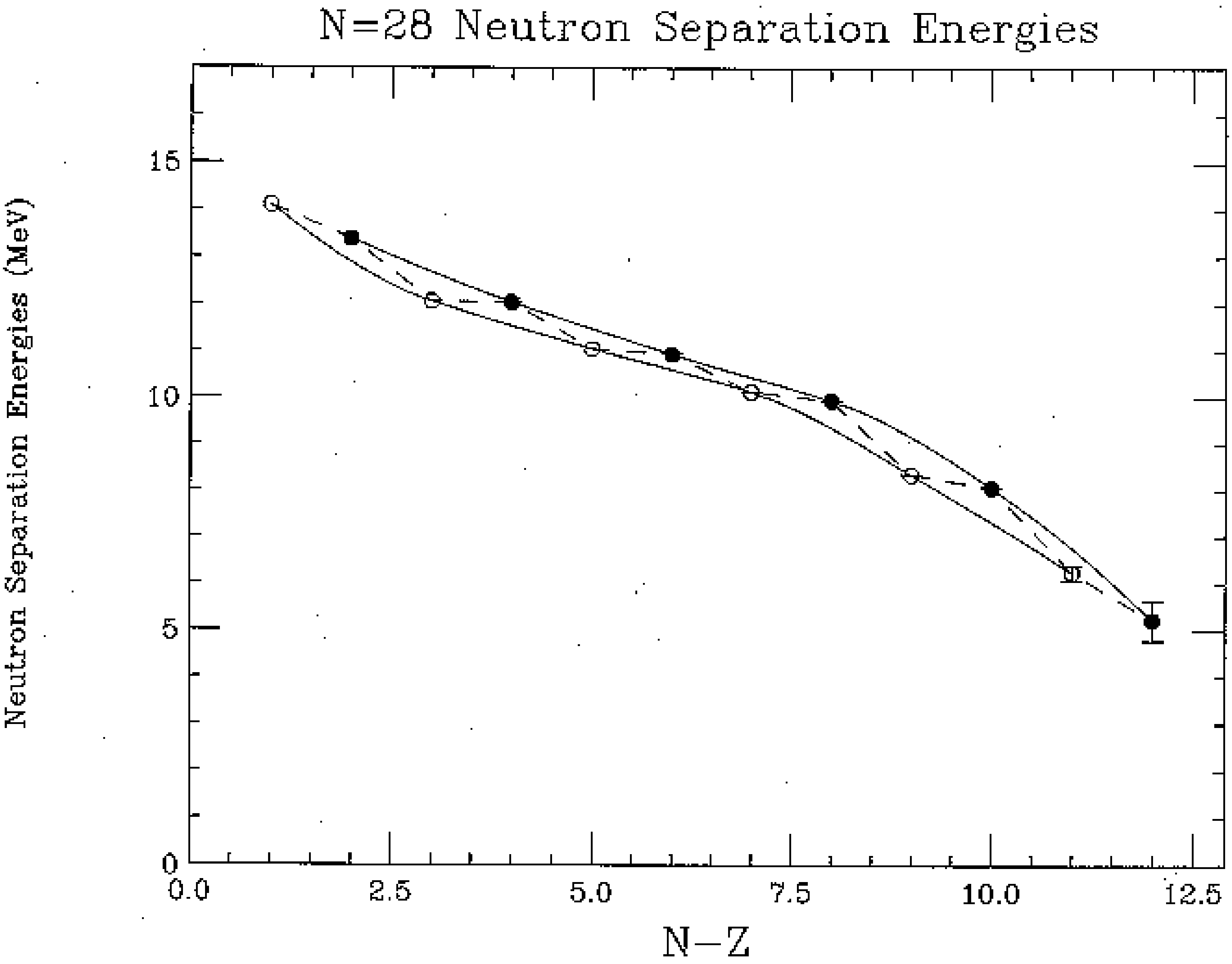
- Need information about neutron separation going to very rich nuclides where production is weak and little is known. Important for r-process and a challenge for microscopic models.

- Abrasion-Ablation "cold fragmentation" efficient in producing the most neutron rich nuclides.

- P-removal chains developed with the fast fragmentation removal of increasing numbers of protons and no loss of neutrons.

- Recent example–production of ^{41}Al (N=28, Z=13) from $48Ca$ with removal of 7 protons. What is the Neutron Separation Energy?


S_n (N Even)for Heaviest Isotope Not Extrapolated
One Neutron Removal Energy (MeV)
0
2
4
6
8
20
25
30
35
40
Z


N=28 Neutron Separation Energies
Neutron Separation Energies (MeV)
N−Z
0
5
10
15
0.0
2.5
5.0
7.5
10.0
12.5

Abrasion-Ablation Model
p-removal chain

Assume the cross section for the removal of x protons consists of two factors one for each stage.

$$\sigma_x = Abr_x \cdot Abl_x \tag{1}$$

where x specifies the number of protons removed.

Abrasion:

Abr_x consists of two factors:

One, providing the cross section for removing x particles, modeled by the the geometrical overlap of projectile with target.

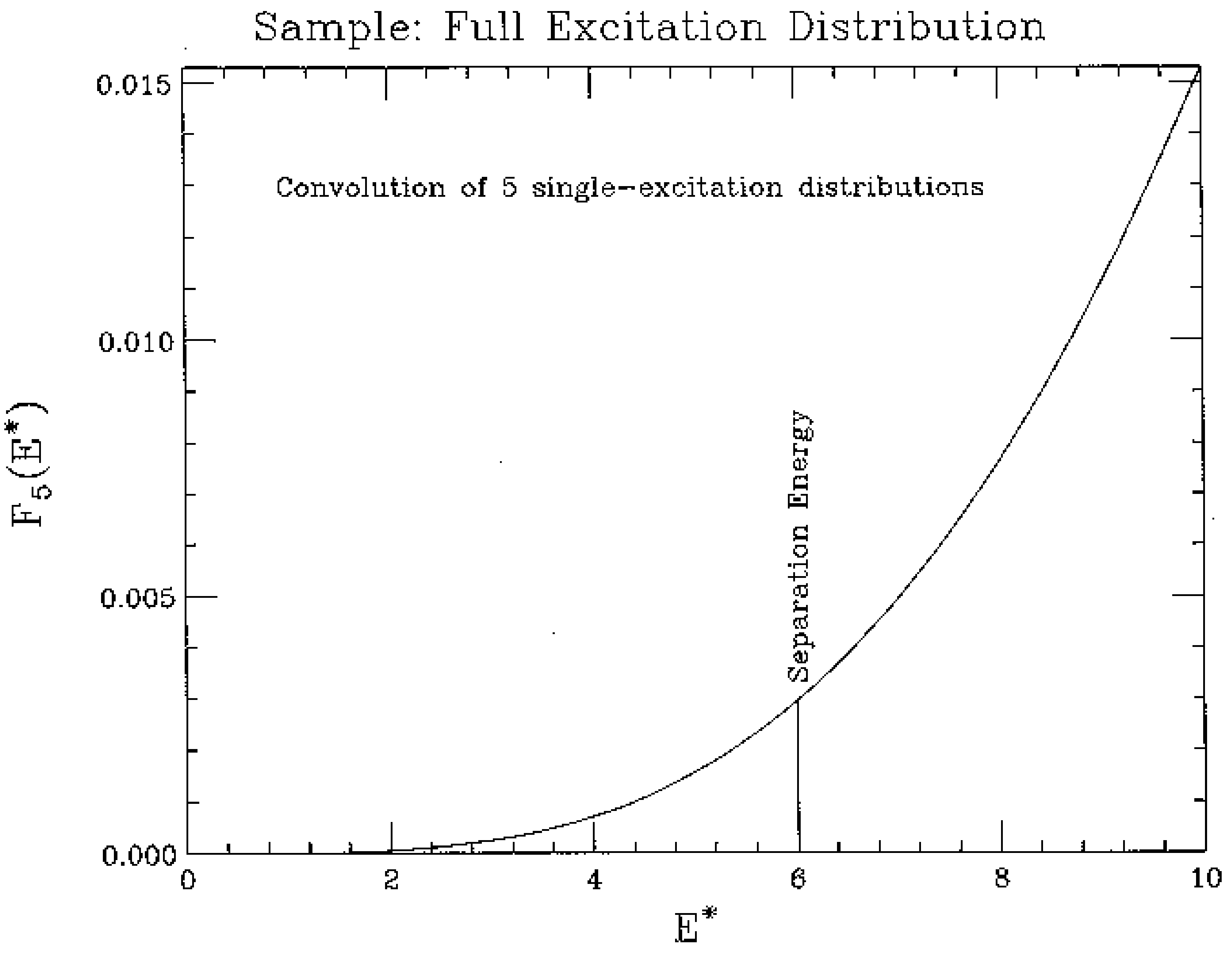
The other, the probablility that all of these be protons, modeled by the uncorrelated statistical factor, $(Z!/(Z-x)!)/((N+Z)!/(N+Z-x)!)$.

The excitation energy of the residue is given by a distribution function $F_x(E^*)$ to be discussed below.

Ablation:

Abl_x gives the probability that no neutron evaporation occurs following the abrasion. It is provided by the integral of $F_x(E^*)$ from zero to *neutron separation energy*.

$$Abl_x = \int_0^{S_n} F_x(E^*) dE^* \tag{2}$$


Sample: Full Excitation Distribution
Convolution of 5 single-excitation distributions
Separation Energy
$F_5(E^*)$
0.015
0.010
0.005
0.000
0
2
4
6
8
10
E^*

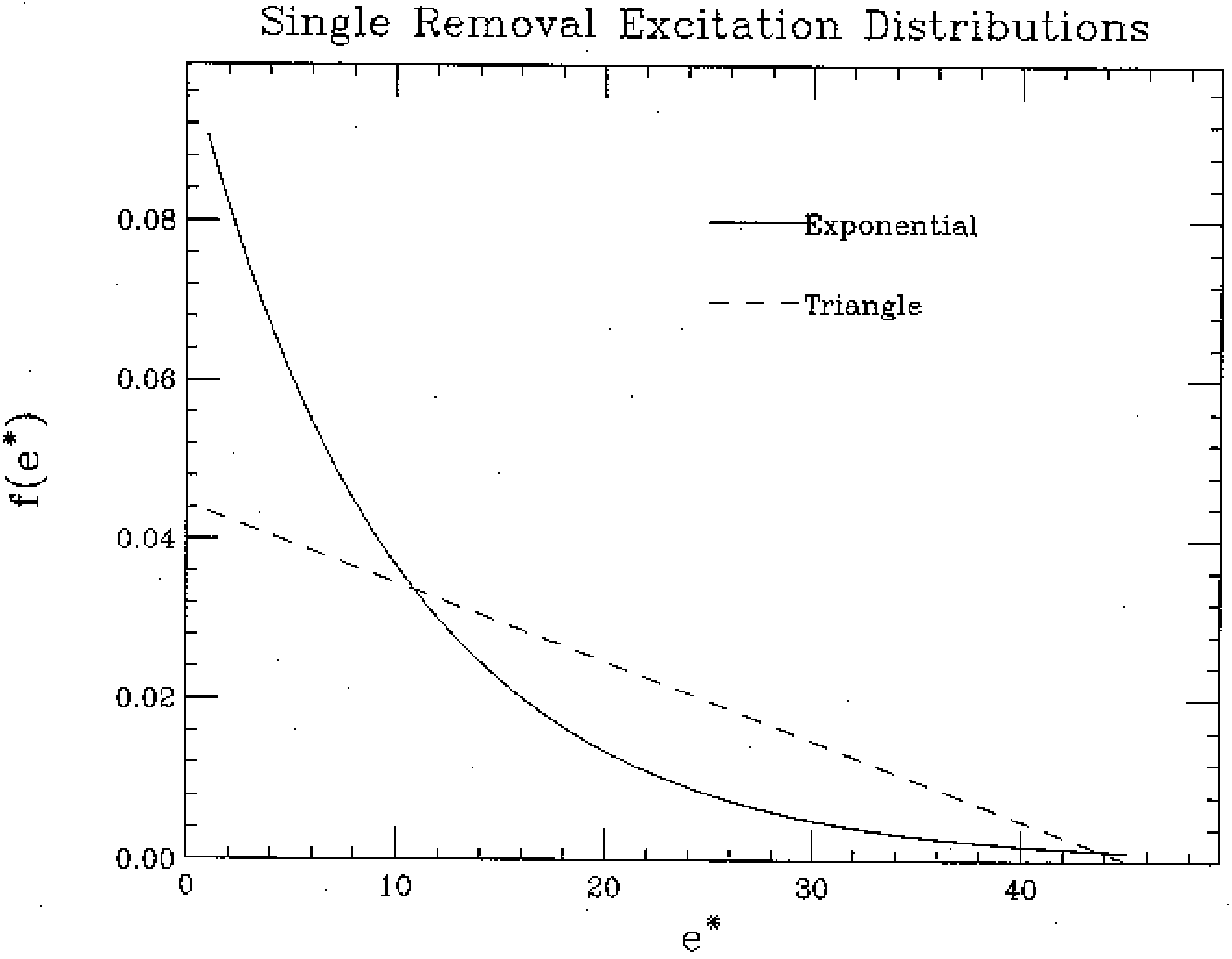
Excitation Energy Distribution

To obtain distribution function for the excitation energy $F_x(E^*)$ following the the removal of x protons, we assume a convolution of x distribution functions for the removal of a single proton, $f_1(e^*)$:

$$F_x(E^*) = \int \prod_{i=1}^{x} (de_i^* \; f_1(e_i^*)) \; \delta(\sum_{i=1}^{x} e_i^* - E^*) \tag{1}$$

We considered two different distributions, $f_1(e^*)$: one having an *exponential* form, the other having a a *triangle* form. Each is characterized by a respective mean value, $< e^* >$.

The convolution of each of these two forms can be calculated analytically using Fourier transforms to obtain the full excitation distribution $F_x(E^*)$.


Single Removal Excitation Distributions

Two Forms of Abl_x

Triangle distribution

$$Abl_x = C_{tri}(x) \cdot (2S_x/(3 < e^* >))^x/x!, \tag{1}$$

where

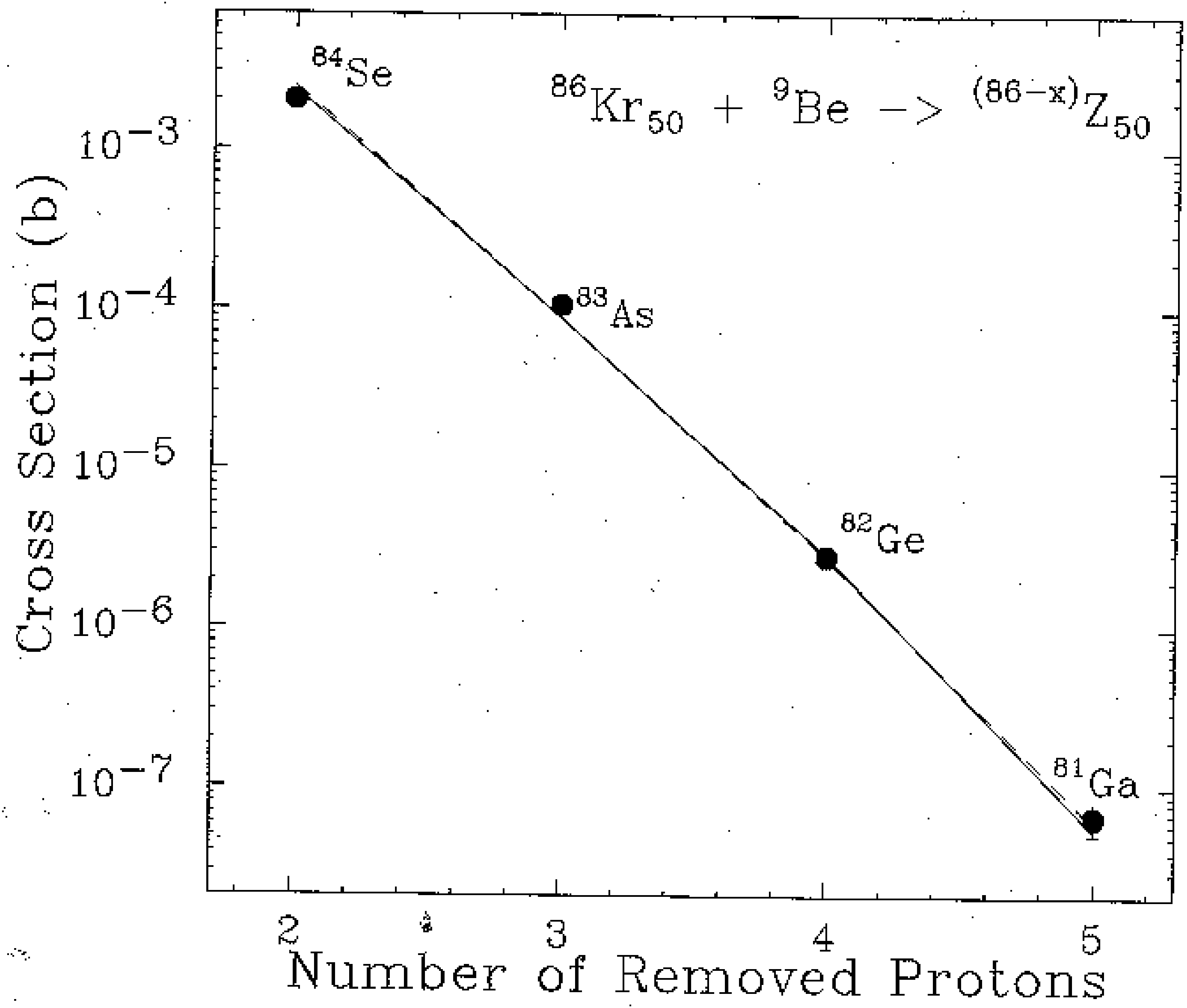
$$C_{\mathrm{tri}}(x) = \sum_{s=0}^{x-s}(-S_x/(3 < e^* >))^s \cdot (x!^2/(s!(x+s)!(x-s)!)) \tag{2}$$

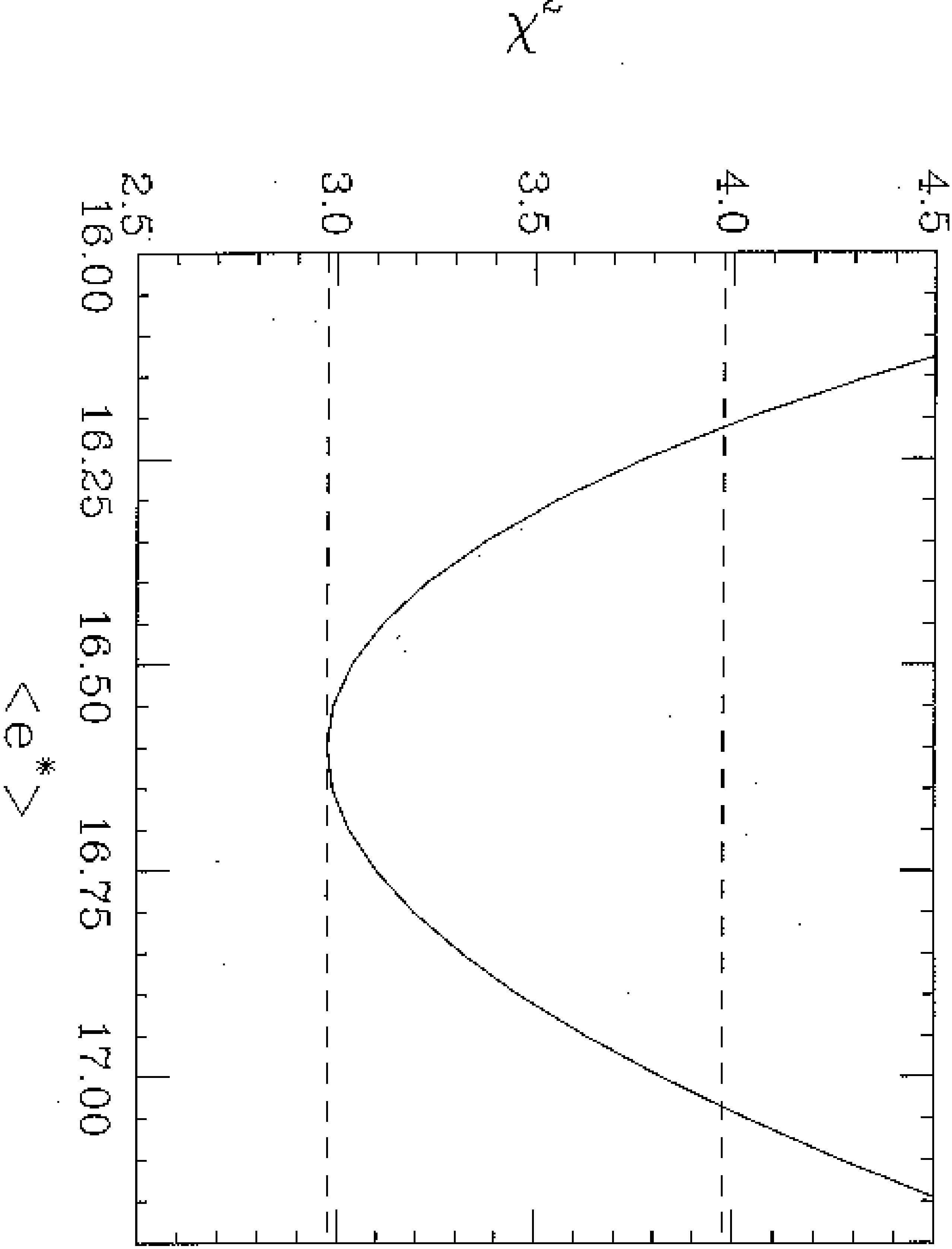
Exponential distribution

$$Abl_x = C_{exp}(x) \cdot (S_x/ < e^* >)^x/x!, \tag{3}$$

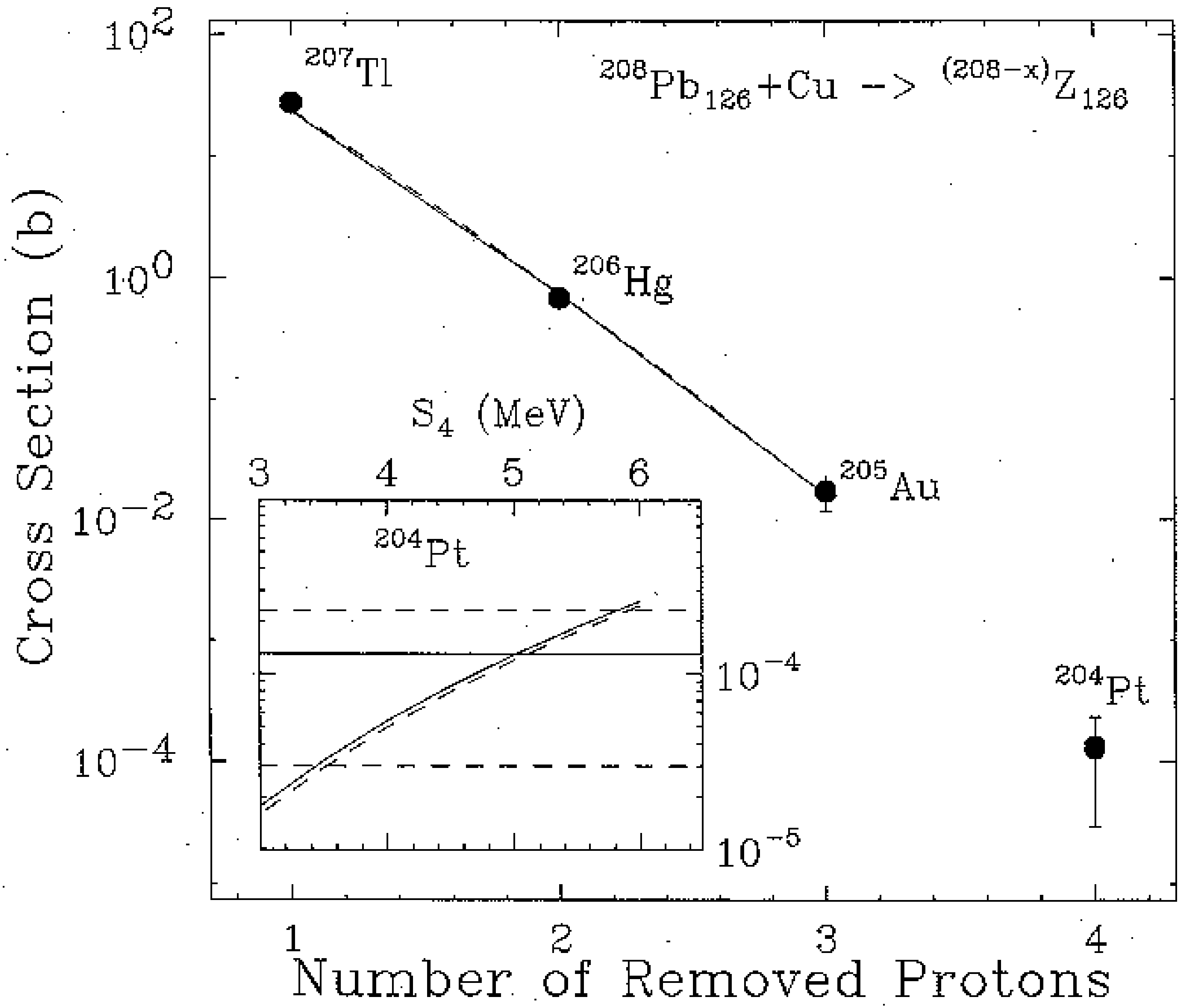
where

$$C_{exp}(x) = \sum_{s=0}(-S_x/ < e^* >)^s(x/((x+s)s!)) \tag{4}$$

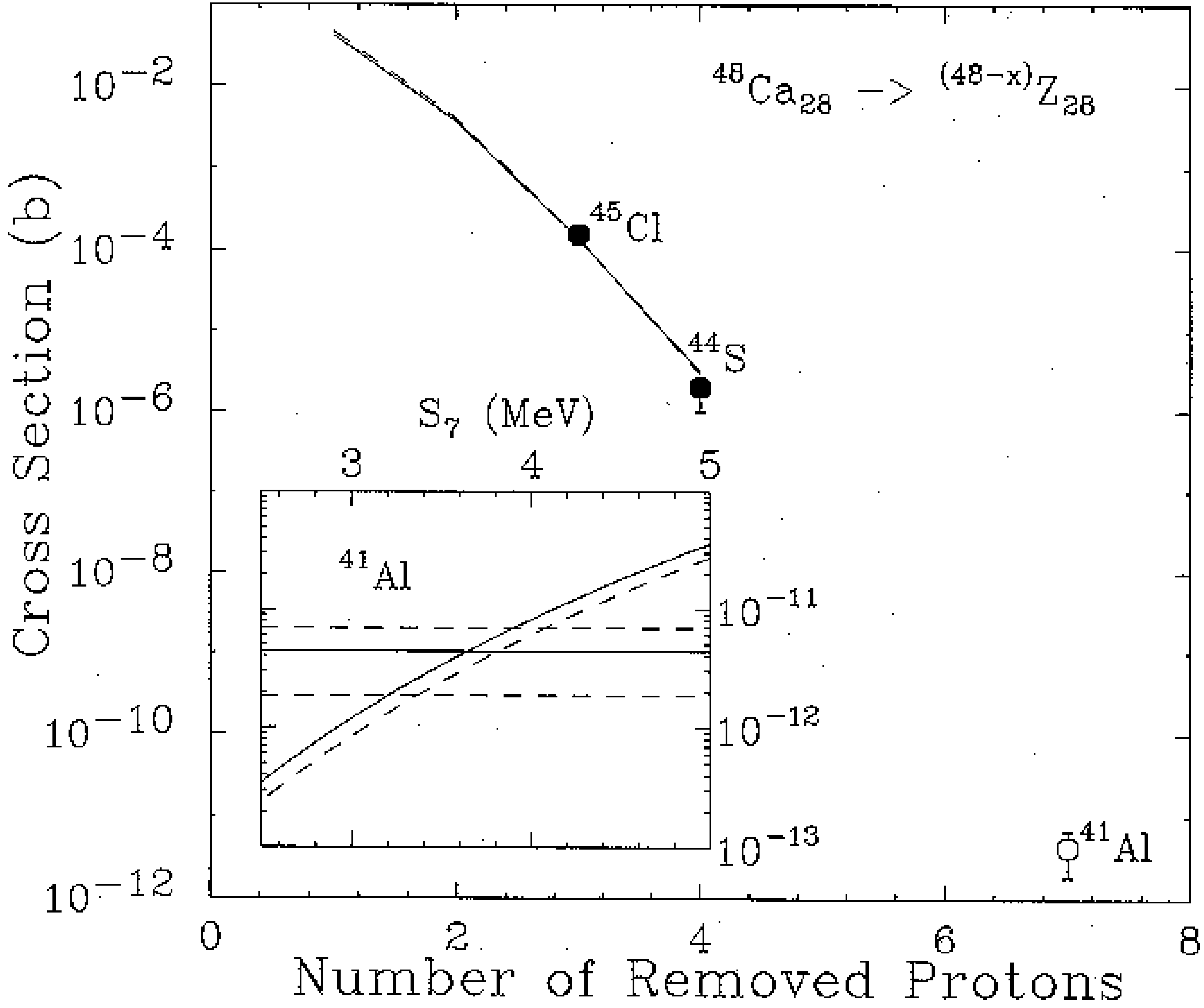

$^{86}Kr_{50} + {}^{9}Be -> {}^{(86-x)}Z_{50}$
^{84}Se
^{83}As
^{82}Ge
^{81}Ga
Cross Section (b)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
2
3
4
5
Number of Removed Protons

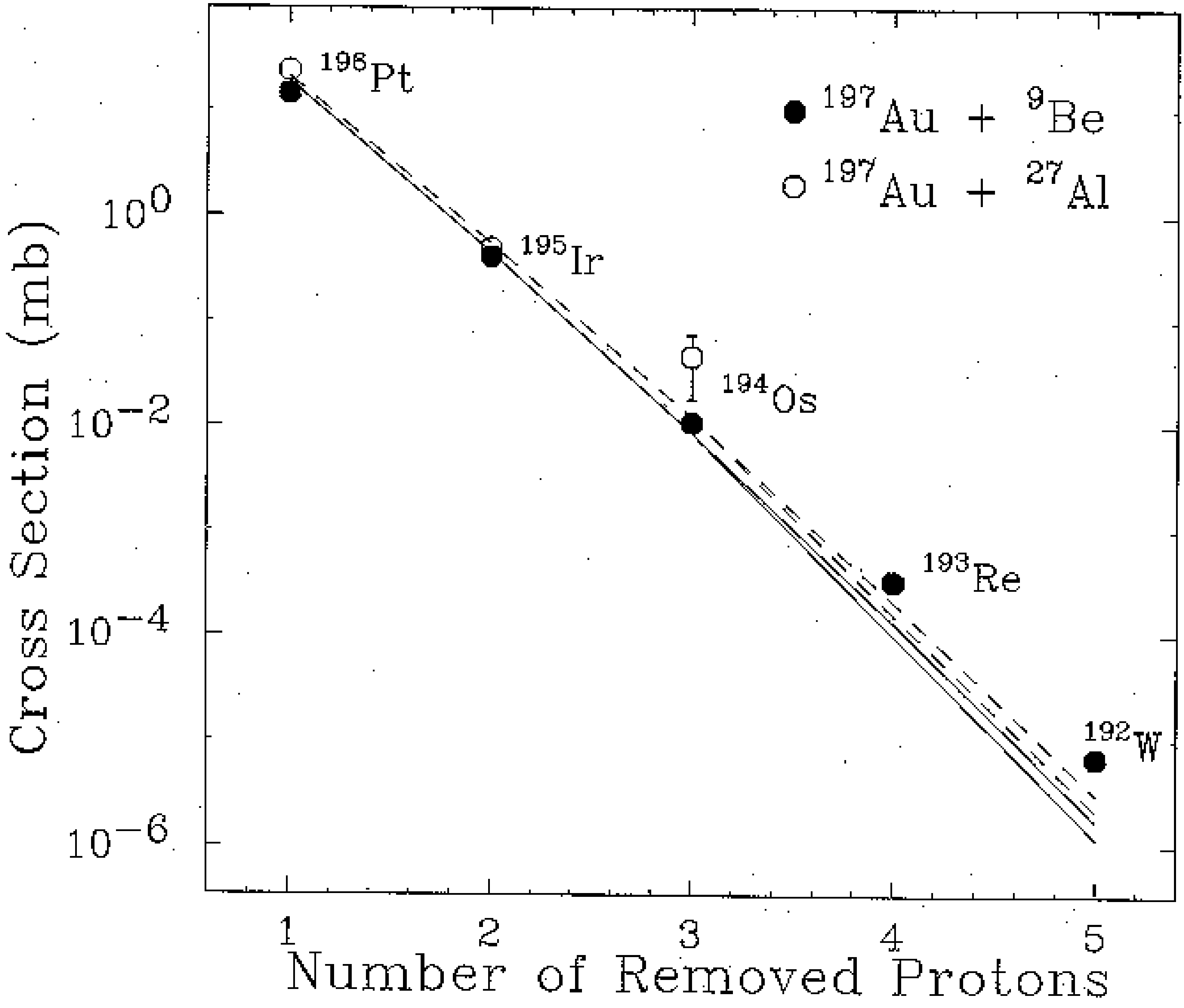

χ^2
4.5
4.0
3.5
3.0
2.5
16.00
16.25
16.50
16.75
17.00
<e*>

Reaction	χ^2/dof tri.	$< e^* >$ tri.	-	+	χ^2/dof exp.	$< e^* >$ exp.	-	+
$^{208}Pb + Cu$[19]	0.38	18.4	1.1	1.5	0.42	26.6	1.8	2.1
$^{197}Au +^{27} Al$[22]	0.87	22.4	1.6	3.6	0.88	32.2	3.8	5.2
$^{197}Au +^{9} Be$[10]	1.87	25.0	1.4	1.8	1.58	36.3	2.2	2.6
$^{136}Xe +^{9} Be$[22]	0.36	23.8	2.8	2.6	0.36	34.2	3.8	5.6
$^{86}Kr +^{9} Be$[16]	1.45	11.7	0.3	0.25	0.99	16.6	0.4	0.45
$^{48}Ca +^{9} Be$[20]	1.24	7.70	0.35	0.4	1.81	10.80	0.45	0.60

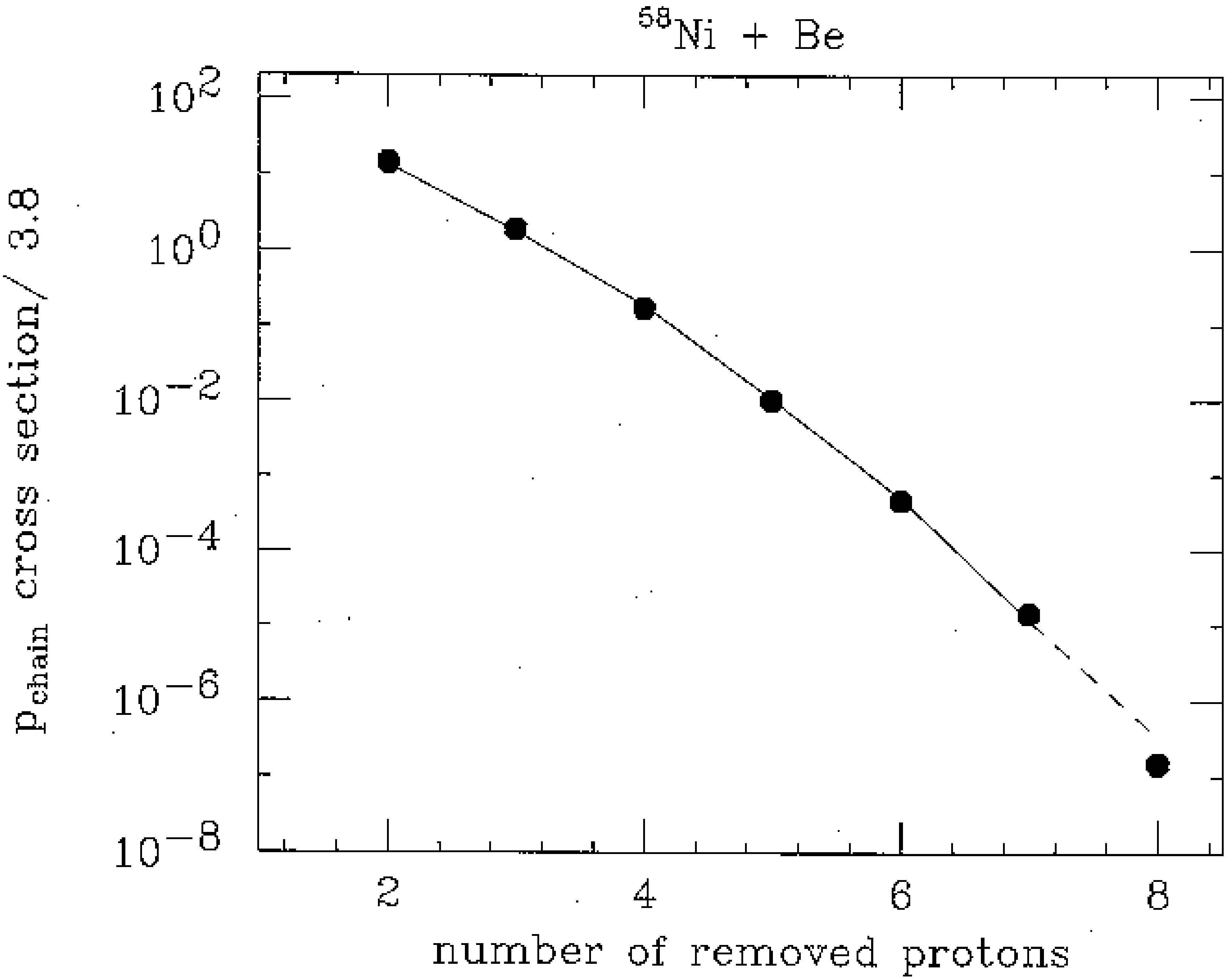


Cross Section (b)
10^{2}
10^{0}
10^{-2}
10^{-4}
^{207}Tl
^{206}Hg
^{205}Au
^{204}Pt
^{208}Pb$_{126}$+Cu -> $^{(208-x)}$Z$_{126}$
S_4 (MeV)
3
4
5
6
^{204}Pt
10^{-4}
10^{-5}
1
2
3
4
Number of Removed Protons

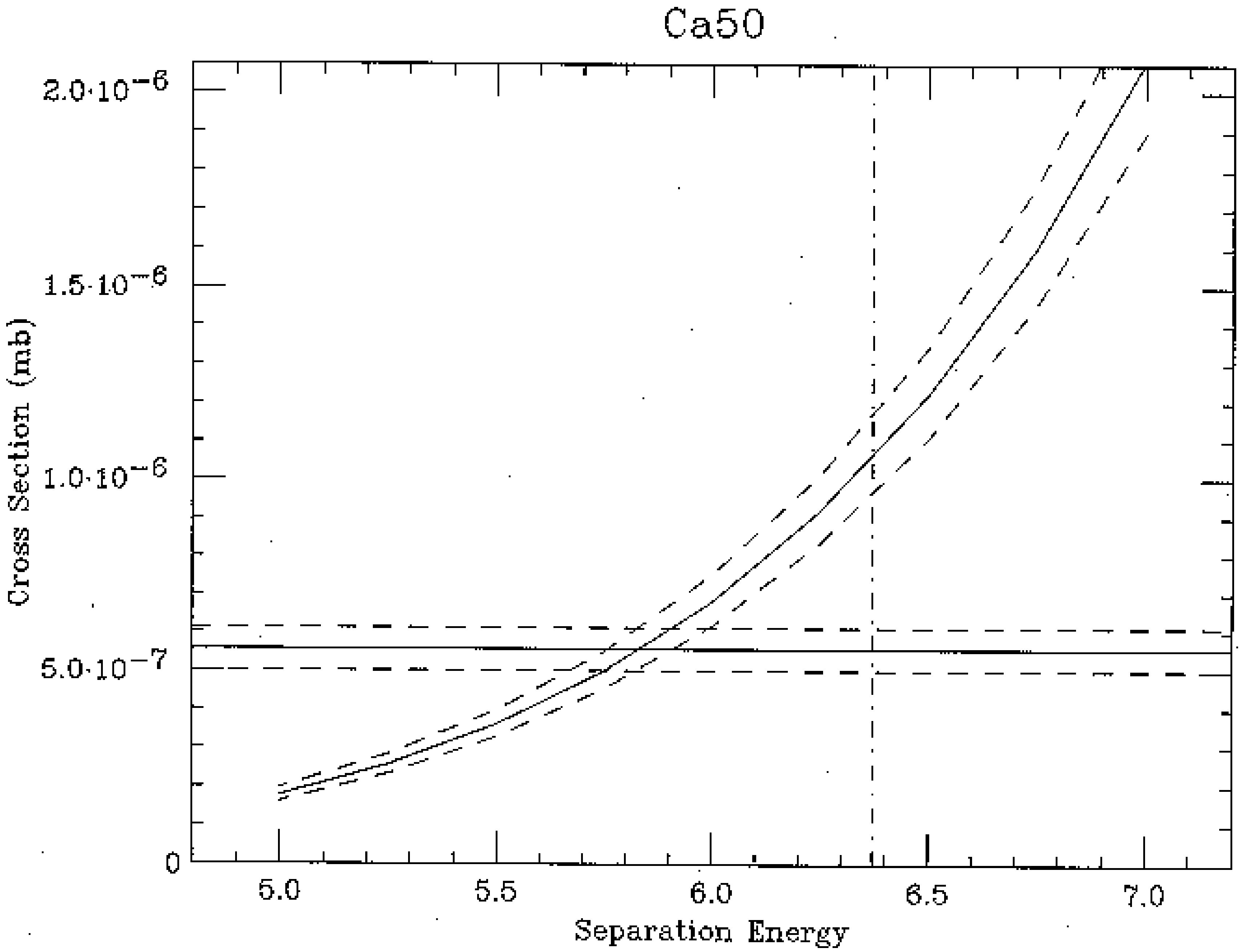

Cross Section (b)
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹²
0
2
4
6
8
Number of Removed Protons
⁴⁸Ca₂₈ -> ⁽⁴⁸⁻ˣ⁾Z₂₈
⁴⁵Cl
⁴⁴S
⁴¹Al
S₇ (MeV)
3
4
5
⁴¹Al
10⁻¹¹
10⁻¹²
10⁻¹³

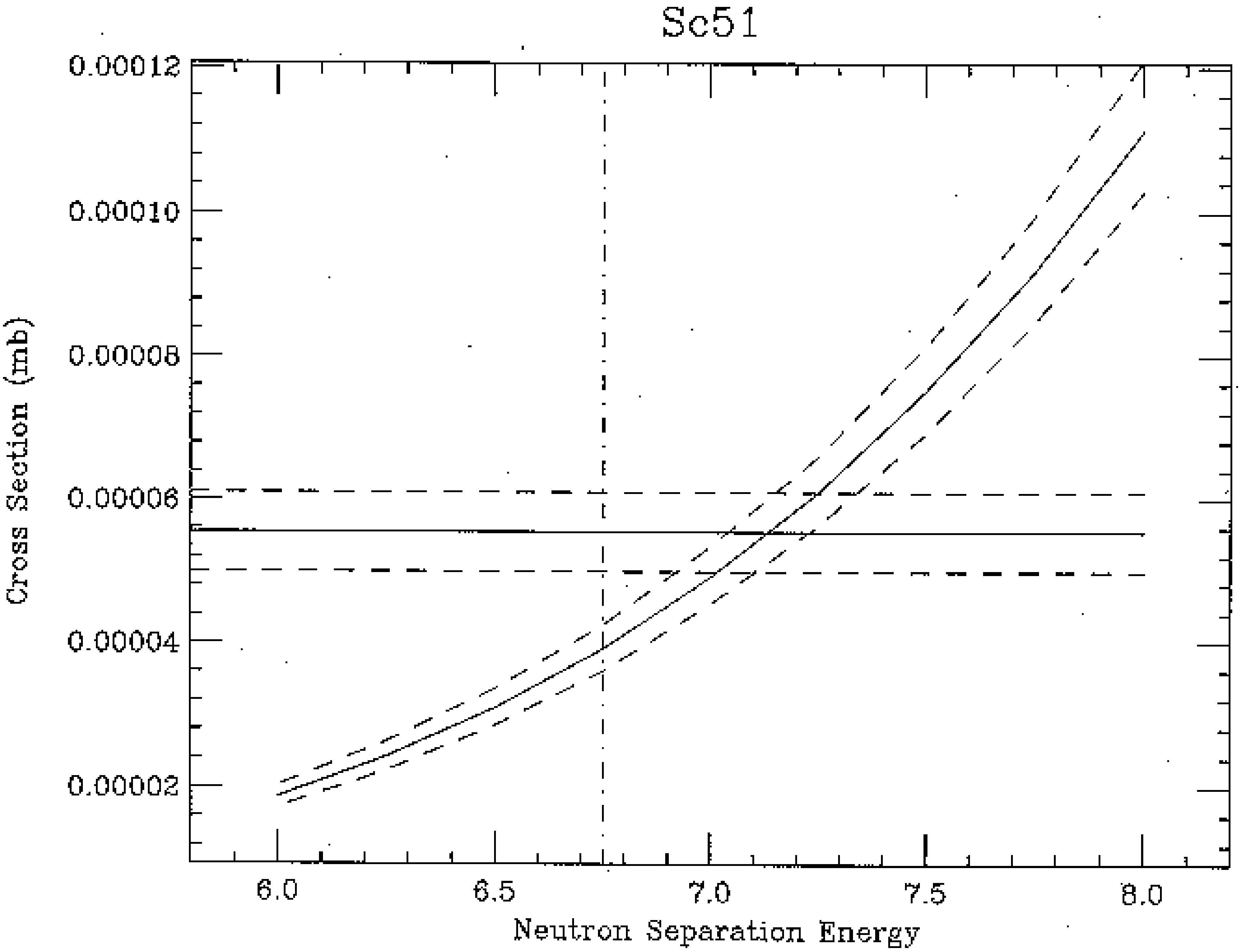


Cross Section (mb)
10^{0}
10^{-2}
10^{-4}
10^{-6}
1
2
3
4
5
Number of Removed Protons
^{196}Pt
^{195}Ir
^{194}Os
^{193}Re
^{192}W
● ^{197}Au + ^{9}Be
○ ^{197}Au + ^{27}Al



^{58}Ni + Be
p_{chain} cross section/ 3.8
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
2
4
6
8
number of removed protons


Ca50
Cross Section (mb)
2.0·10^-6
1.5·10^-6
1.0·10^-6
5.0·10^-7
0
5.0
5.5
6.0
6.5
7.0
Separation Energy


Sc51
0.00012
0.00010
0.00008
0.00006
0.00004
0.00002
Cross Section (mb)
6.0
6.5
7.0
7.5
8.0
Neutron Separation Energy

n-removal chains

The situation for reaching proton rich nuclides by n-removal is quite different concerning the measurement of proton removal energies.

- Coulomb barriers affect the practical threshold for protons.
- Neutrons can be removed by both the abrasion process and also by evaporation (which can strongly compete with the proton evaporation).
- Abrasion-Ablation model can predict n-removal chains but this involves model dependent complications (coulomb barrier, and evaporation treatment) which are absent in the p-removal chains.

Conclusions

1. Illustrated examples show simple Abrasion-Ablation model for p-removal chains provides excellent agreement with fragment cross sections.

2. The calculated cross sections depends on an excitation parameter ($< e^* >$) and neutron separation energy.

3. Each p-removal chain seems to be characterized by a single $< e^* >$, which can be fit. Equally good fits are obtained with *Triangle* and *Exponential* distributions. (Mean energies approximately 2:3)

4. From some of the data in the the literature we suggest the power of the p-removal chains for observing unknown separation energies for ^{204}Pt and ^{41}Al in different chains.

5. Some puzzling disagreement appears in ^{197}Au data.

6. Ongoing work with ^{58}Ni with a measured chain up 8 protons, suggests further success. Comparison with with known separation energies, suggest a precision for the neutron separation energy of a few hundred keV.

7. Neutron removal chains are more uncertain regarding proton separation energies.

8. Work is ongoing to understand the variation of the energy parameter with projectile choice. This can suggest the situations in which longest chains may be measured practically.