FISSION AT FUSTIPEN II: RECENT OBSERVABLES AND THEIR MODELING, MAY 2–3, 2016, GANIL, CAEN, FRANCE

Fission yields versus both Z and N in the Brownian Shape Motion method for U and Pu

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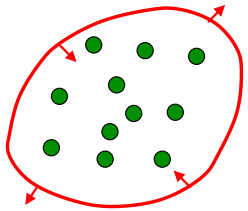
Collaborators on this and other projects:
W. D. Myers, J. Randrup (LBNL), H. Sagawa (Aizu), S. Yoshida (Hosei), T. Ichikawa(YITP), A. J. Sierk(LANL), A. Iwamoto (JAEA), S. Aberg (Lund), R. Bengtsson (Lund), S. Gupta (IIT, Ropar), and many experimental groups (e. g. K.-L. Kratz (Mainz), H. Schatz (MSU), A. Andreyev (York), K. Nishio (JAEA), Christelle Schmitt, GANIL . . .).

More details about fission, other projects, additional collaborators associated ASCII data files, interactive access to data (type in Z, A and get specific data, contour maps) and figures are at

http://t2.lanl.gov/nis/molleretal/



Brownian shape motion

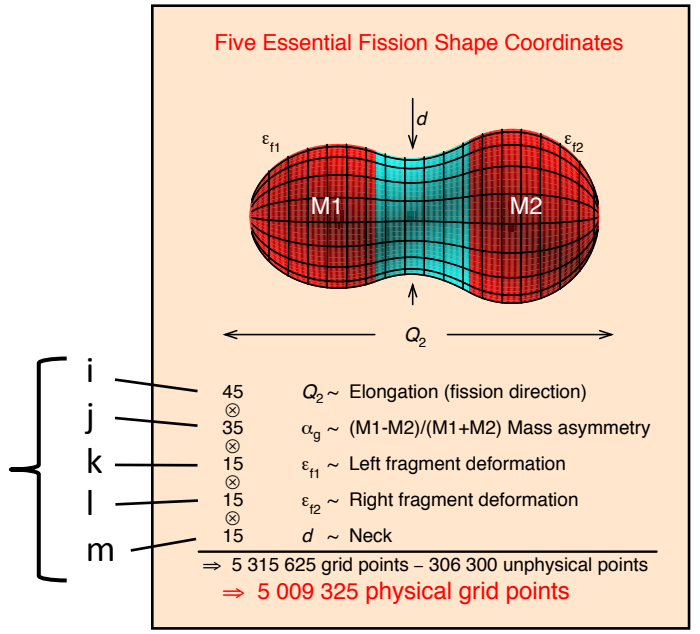
Nuclear deformation energy: $E_{def}(i,j,k,l,m)$

Bias potential: $V_{bias}(i) = V_0\,(Q_0/Q_2)^2$

Level density parameter: $a_A = A/(8\ \text{MeV})$

Temperature T: $E^* - E_{def} = a_A T^2$

$$\Rightarrow\ V(\chi) = E_{def} + V_{bias}$$



P. Möller *et al*, Nature 409 (2001) 785

Metropolis walk:

N. Metropolis *et al*, J Chem Phys 26 (1953) 1087

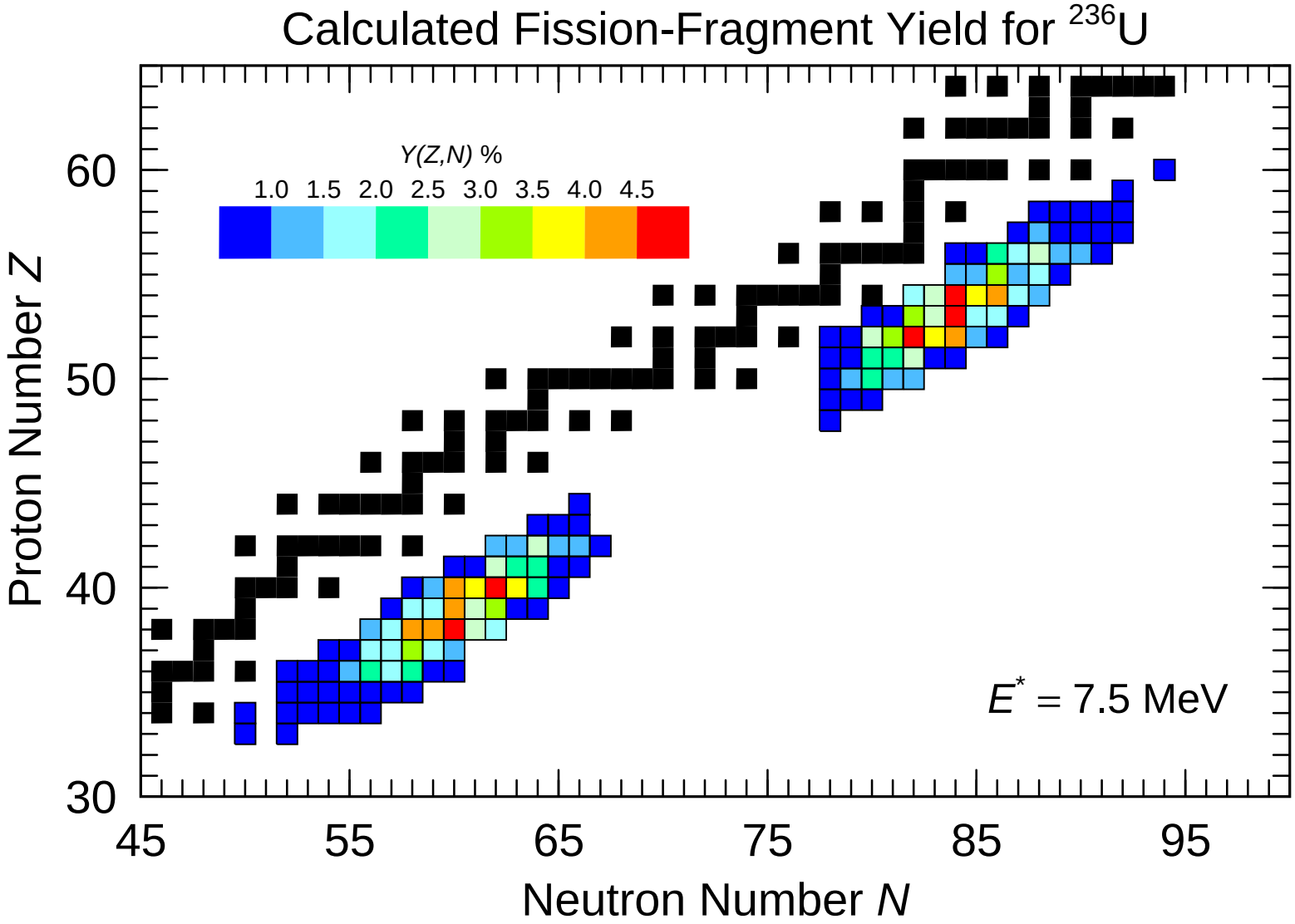
Change shape: $\chi \rightarrow \chi'$?

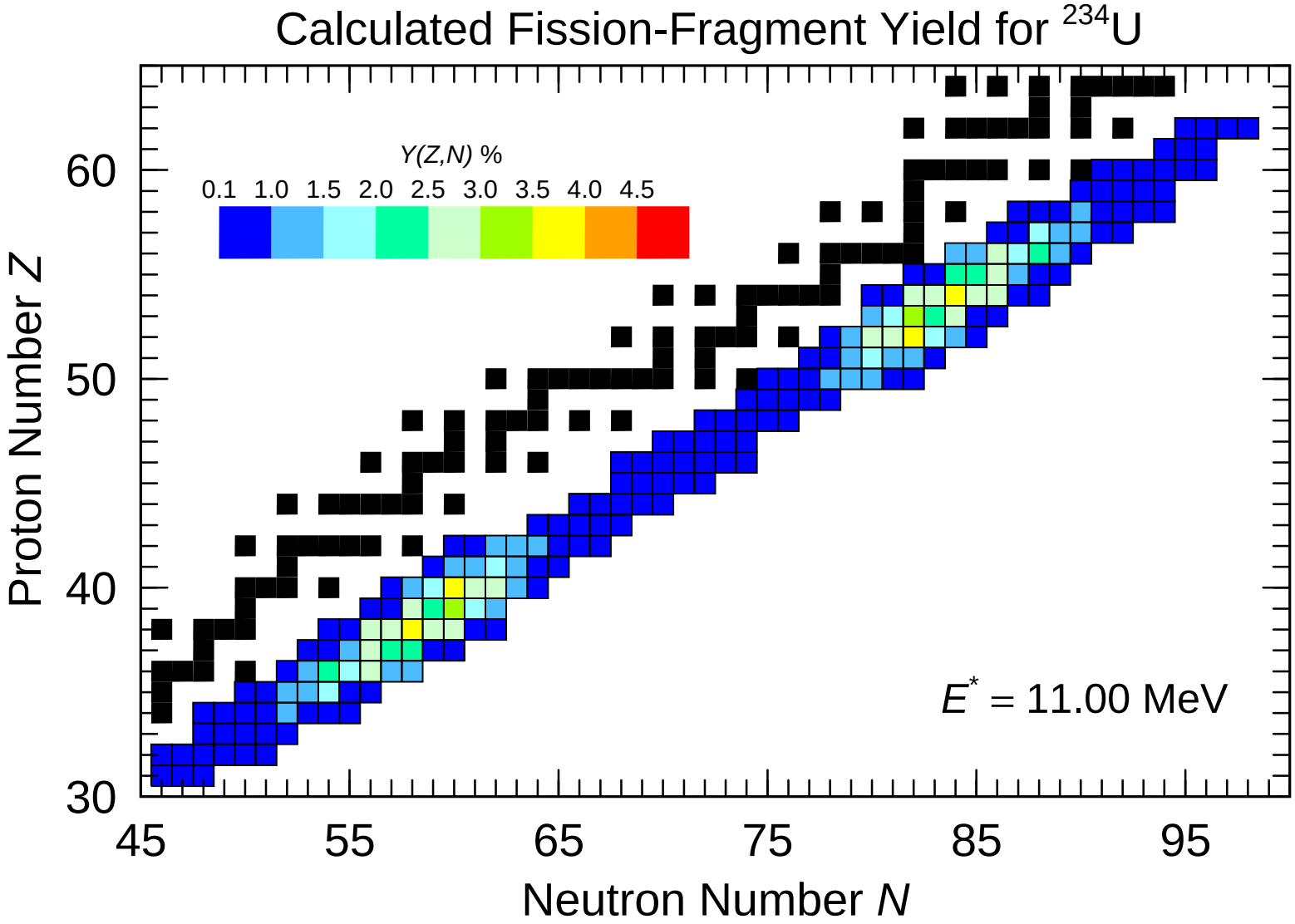
- $V(\chi') < V(\chi)$: *move with* $P = 1$
- $V(\chi') > V(\chi)$: *move with* $P = \exp(-\Delta V/T)$

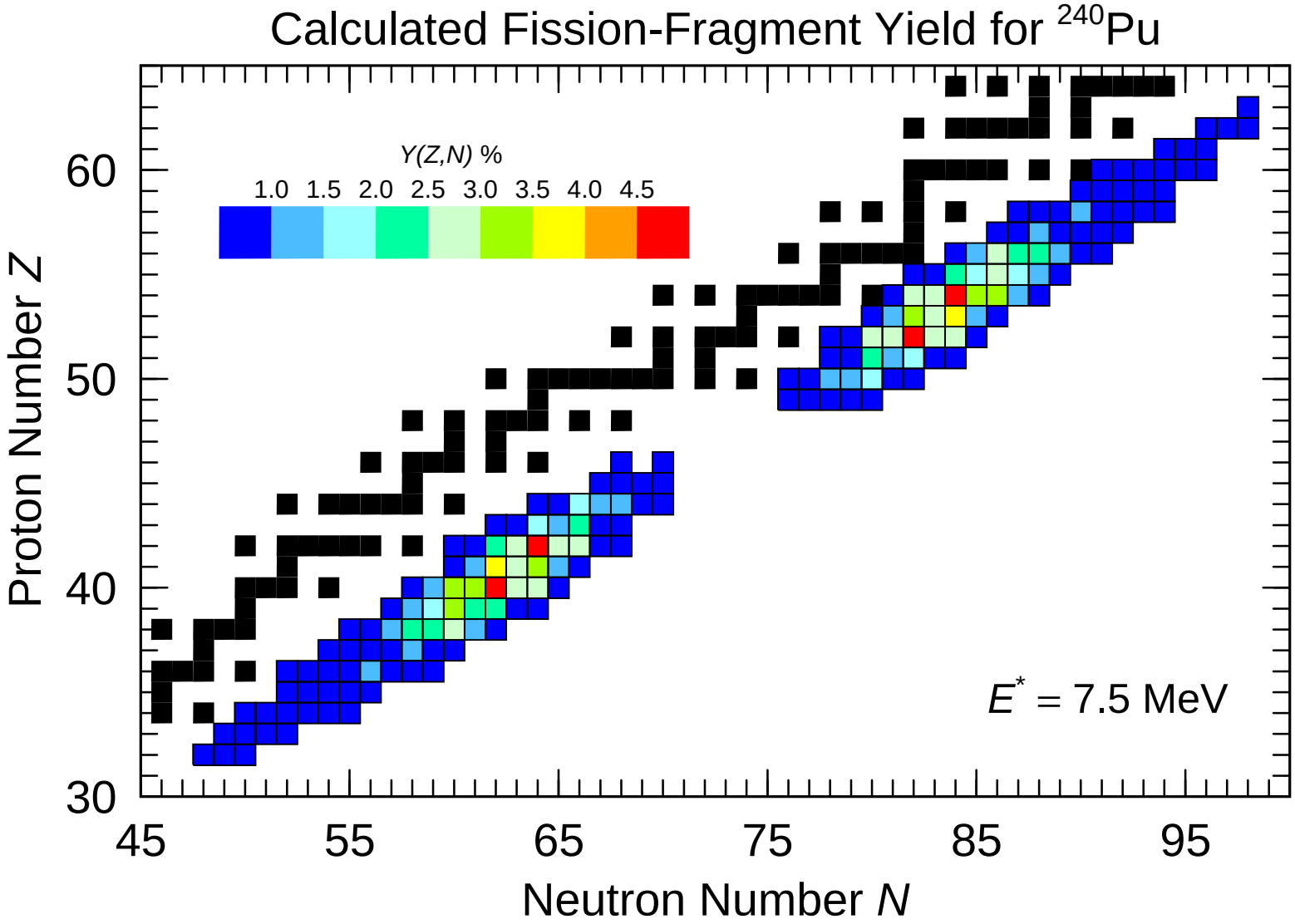
Scission: Critical neck radius $c_0 \approx 2.5$ fm

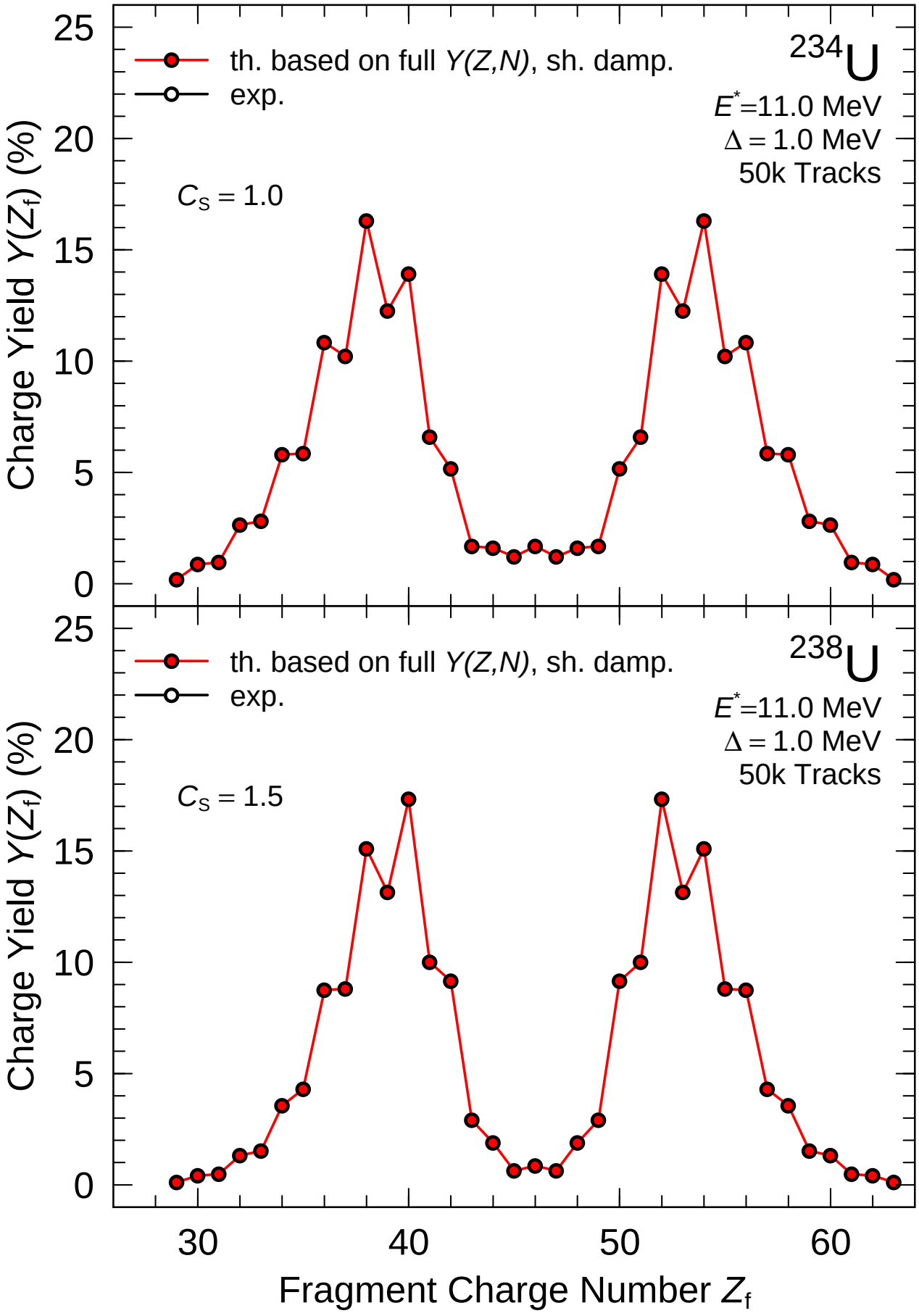
Method for Calculating $E(Q_2, d, \epsilon_{\mathsf{f1}}, \epsilon_{\mathsf{f1}}, Z_1, N_1)$

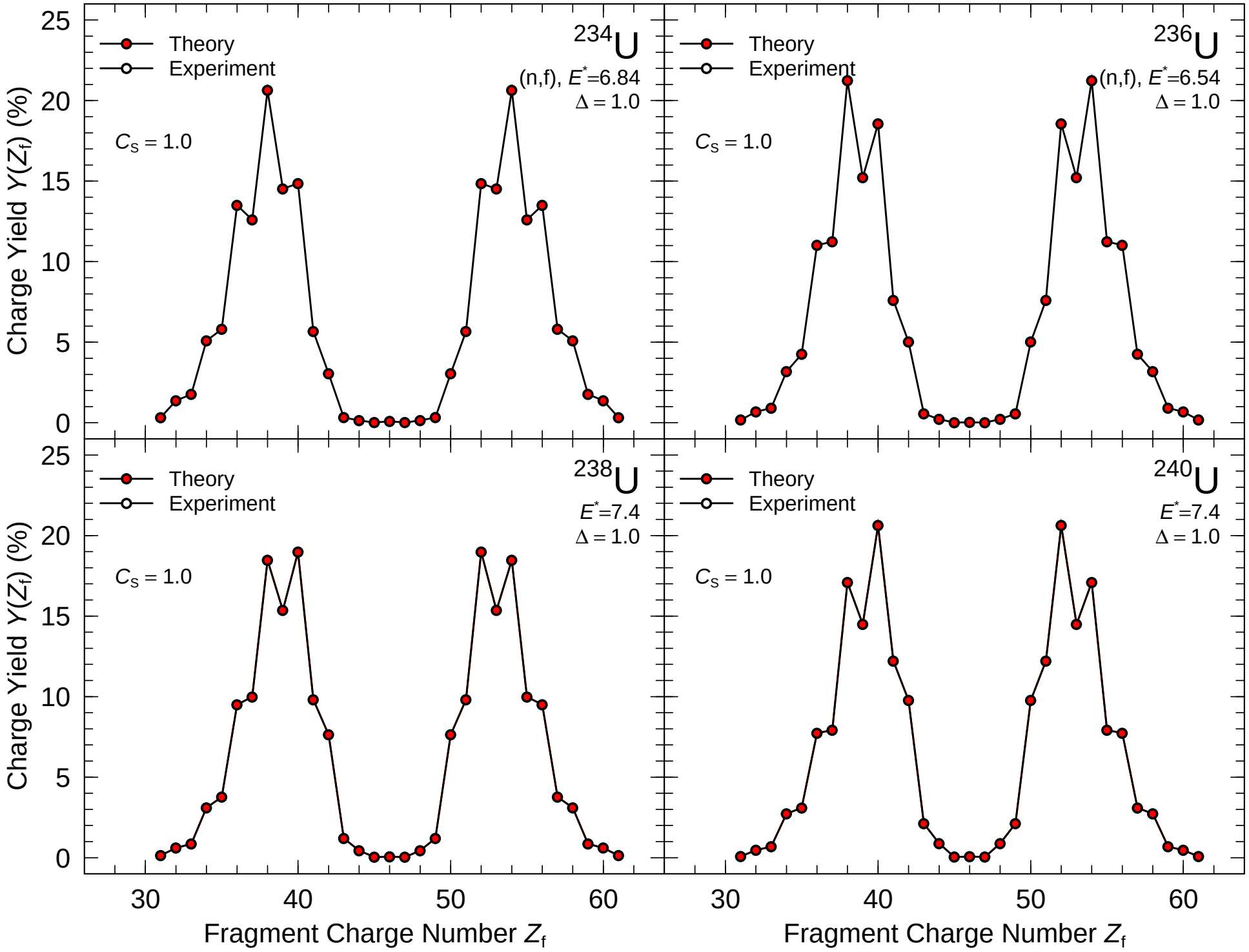
- Calculate $E_{\mathsf{SH,n}}(N_1)$ for integer N_1, save
- Calculate $E_{\mathsf{SH,p}}(Z_1)$ for integer Z_1,
  also save $E_{\mathsf{mac}}(Z_1, N(Z_1))$
- Total energy for $(Z\mathsf{x}, N_\mathsf{x})$ split is then
  $E_{\mathsf{SH,n}}(N_\mathsf{x}) + E_{\mathsf{SH,p}}(Z_\mathsf{x}) + E_{\mathsf{mac}}(Z_\mathsf{x}, N(Z_\mathsf{x})) +$Diff
- Diff obtained from separated fragment Macroscopic energy difference, see
  EPJA-051-2015-173.

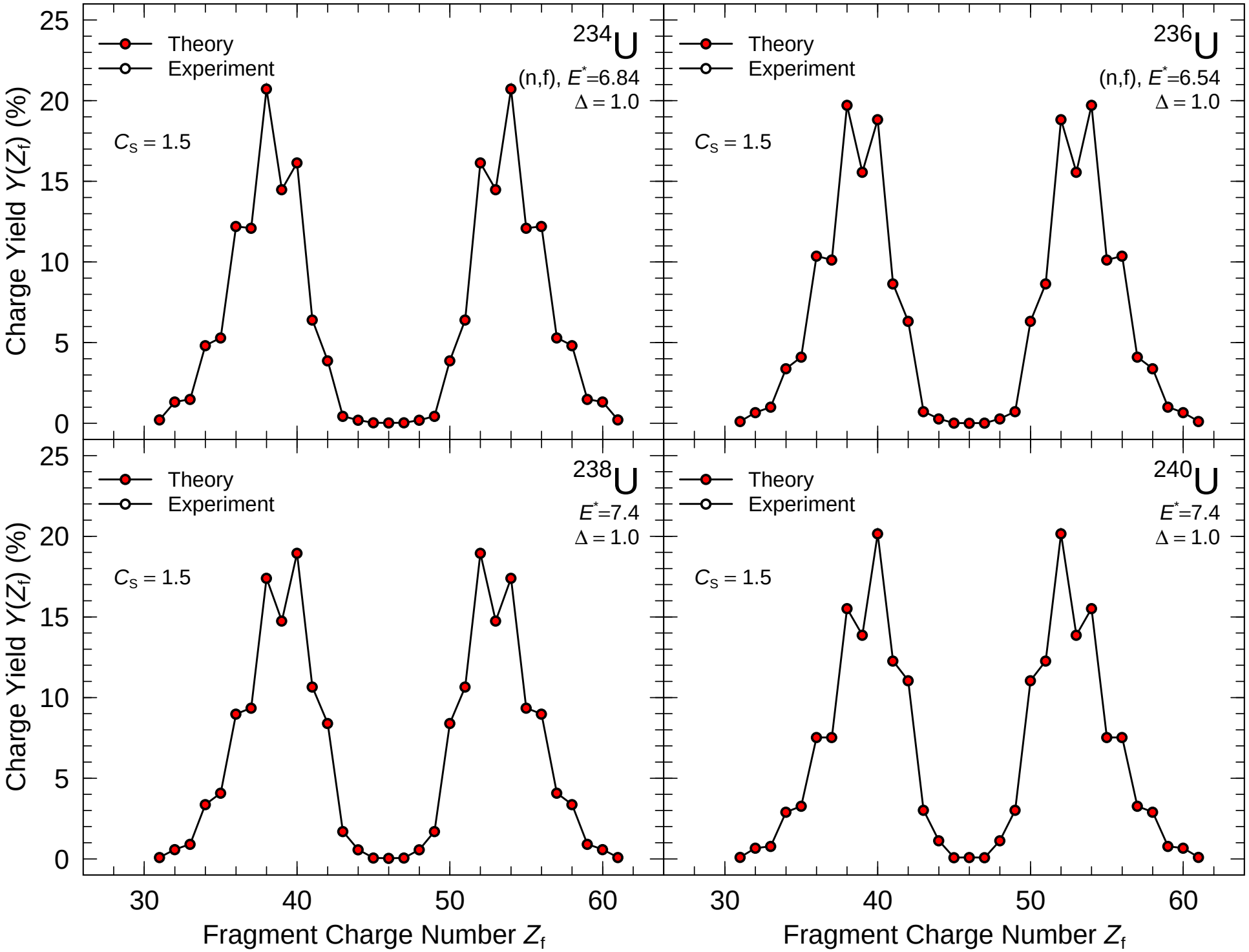

Calculated Fission-Fragment Yield for ^{236}U
Y(Z,N) %
1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
E^* = 7.5 MeV
Proton Number Z
Neutron Number N
30
40
50
60
45
55
65
75
85
95

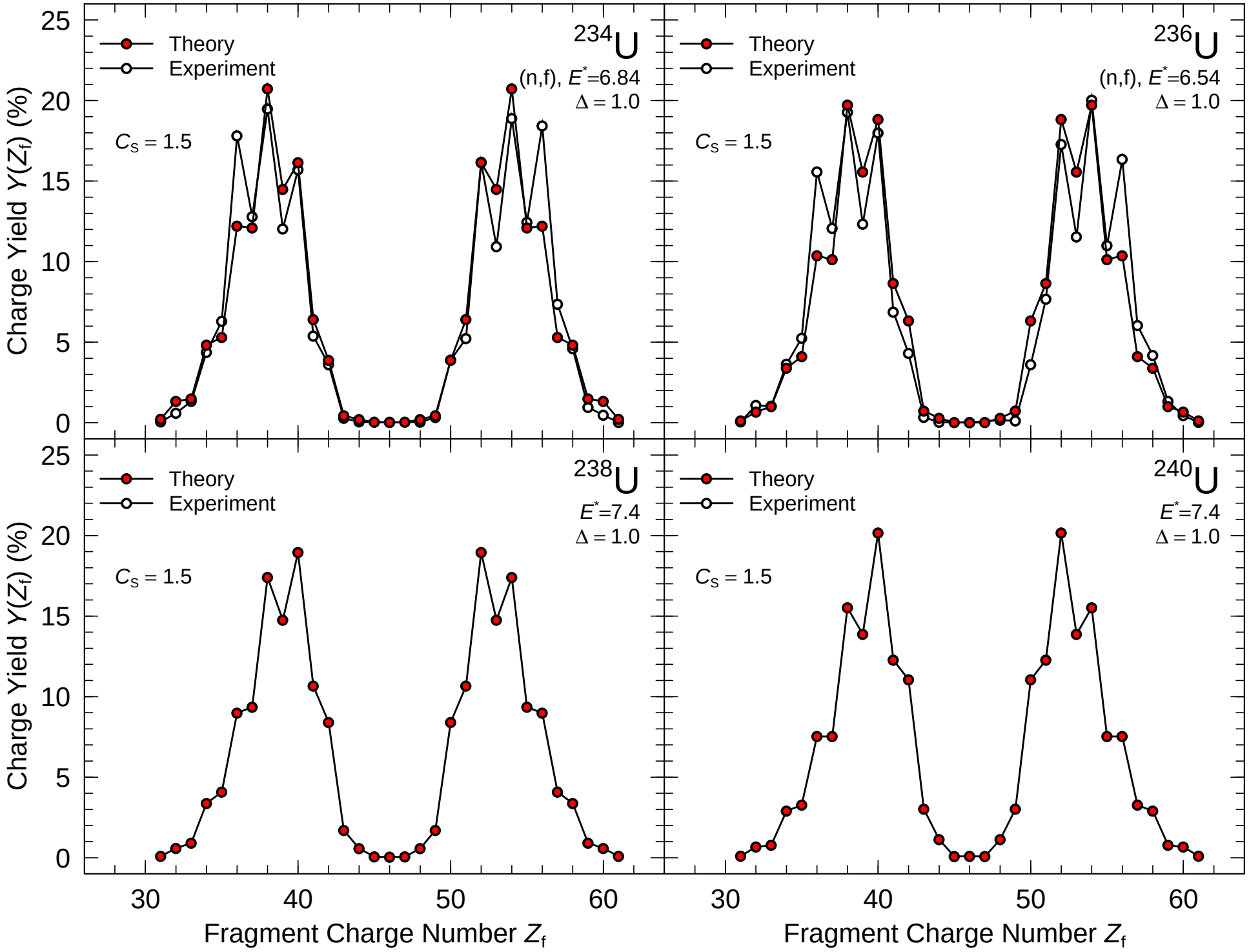

Calculated Fission-Fragment Yield for ^{234}U
Y(Z,N) %
0.1 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
E^* = 11.00 MeV
Proton Number Z
Neutron Number N
30
40
50
60
45
55
65
75
85
95

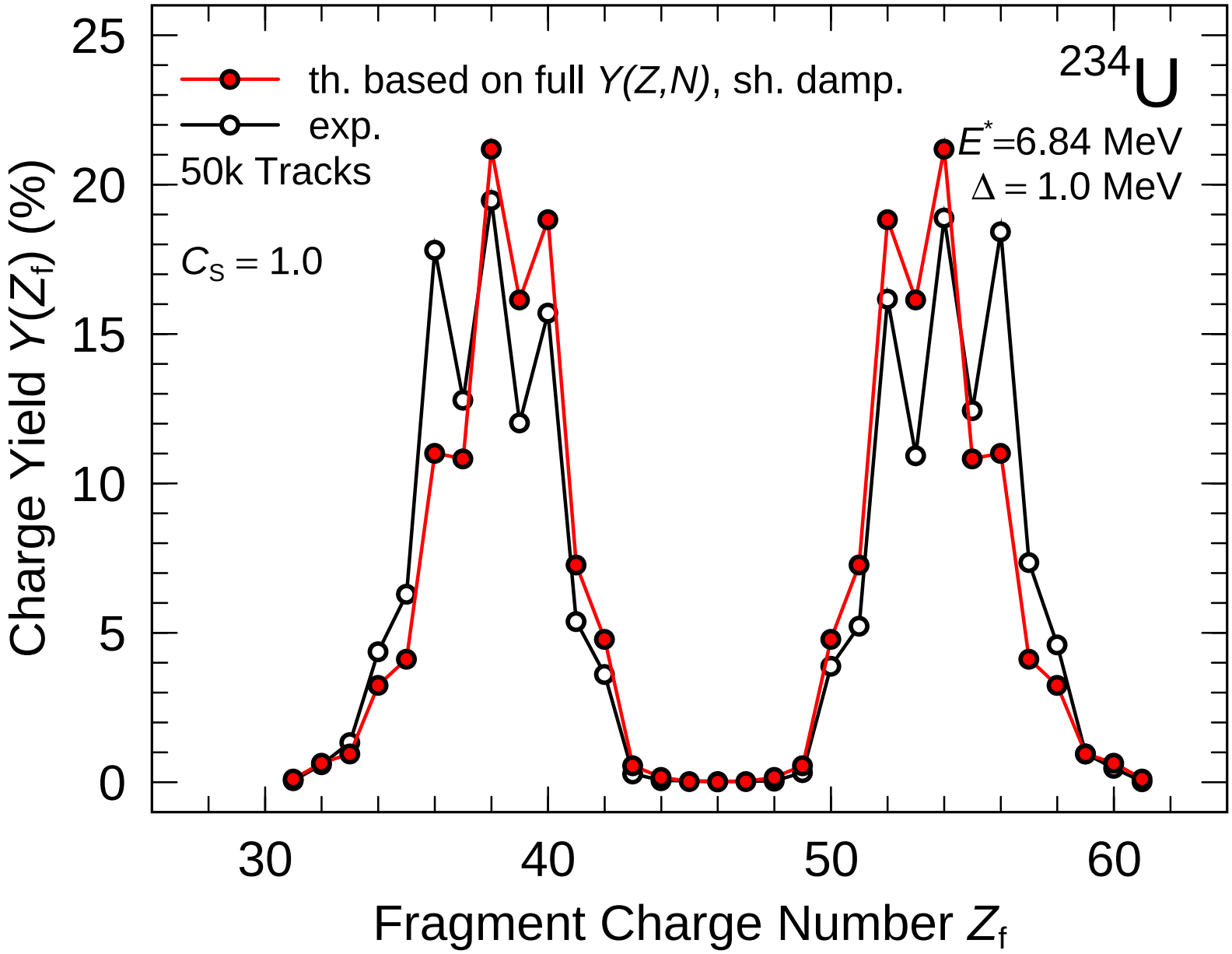

Calculated Fission-Fragment Yield for ^{240}Pu
Y(Z,N) %
1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5
$E^* = 7.5$ MeV
Proton Number Z
Neutron Number N
30
40
50
60
45
55
65
75
85
95

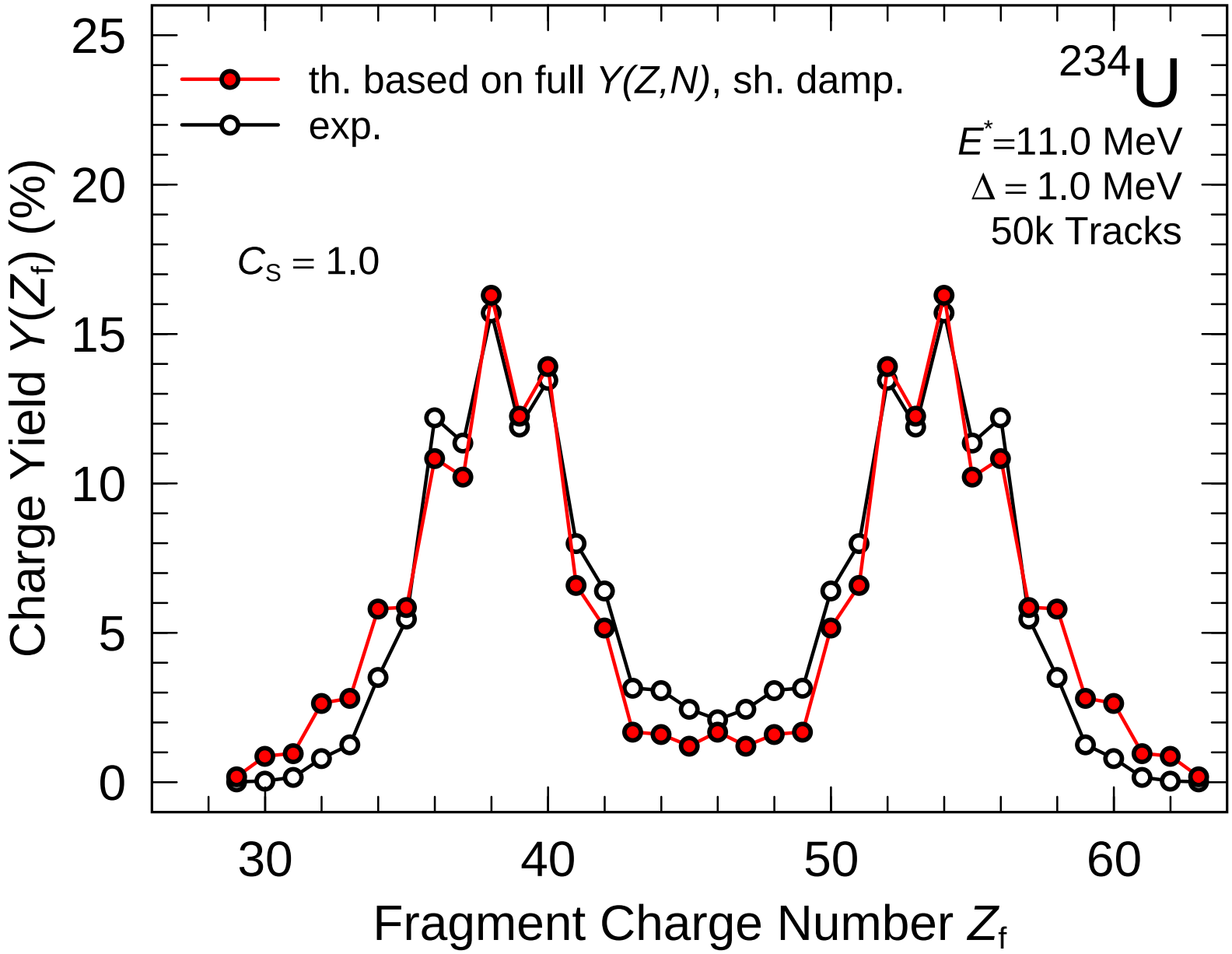

th. based on full Y(Z,N), sh. damp.
exp.
234U
E*=11.0 MeV
Δ = 1.0 MeV
50k Tracks
CS = 1.0
238U
E*=11.0 MeV
Δ = 1.0 MeV
50k Tracks
CS = 1.5
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

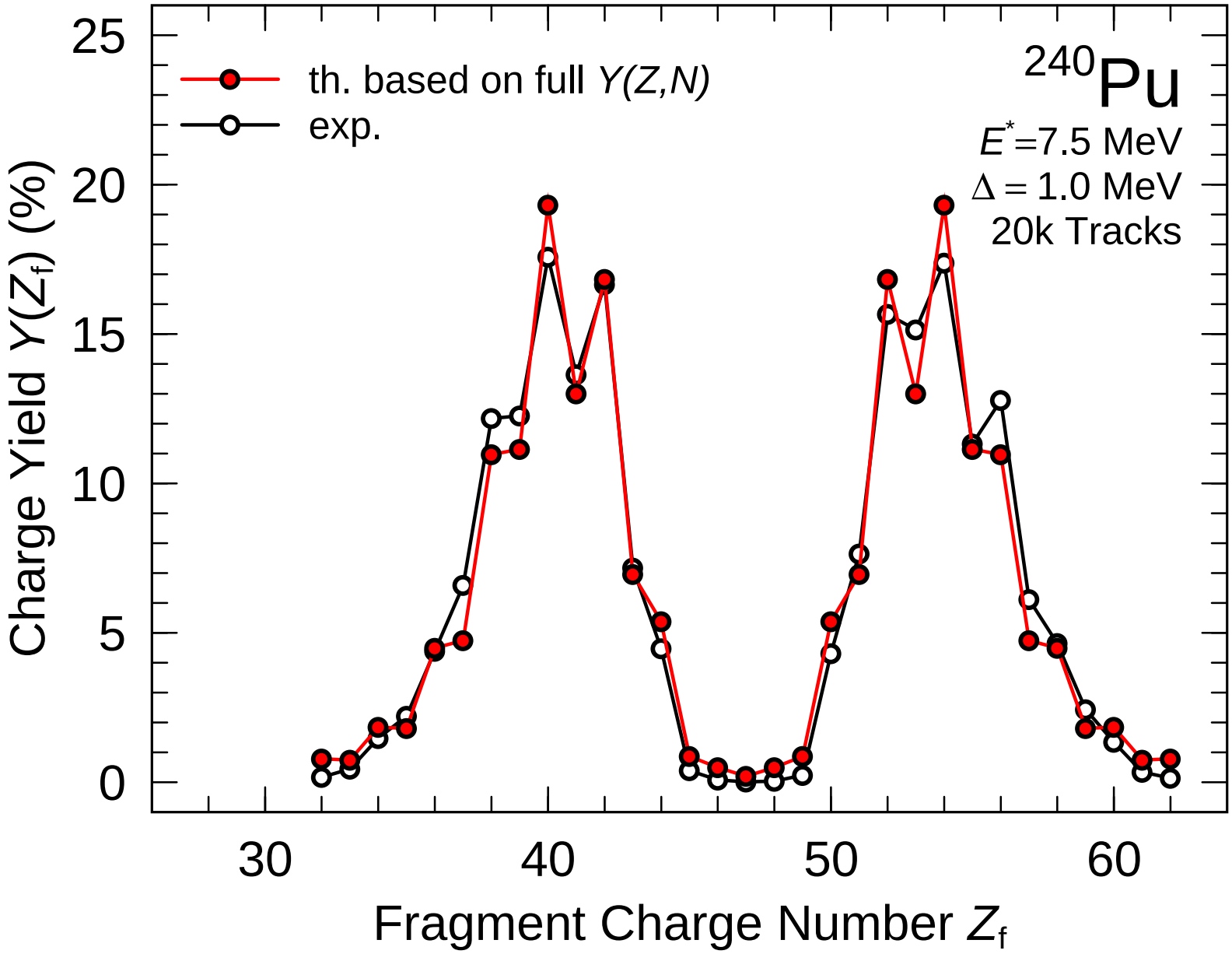

Theory
Experiment
234U
(n,f), E*=6.84
Δ = 1.0
CS = 1.0
236U
(n,f), E*=6.54
Δ = 1.0
CS = 1.0
238U
E*=7.4
Δ = 1.0
CS = 1.0
240U
E*=7.4
Δ = 1.0
CS = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

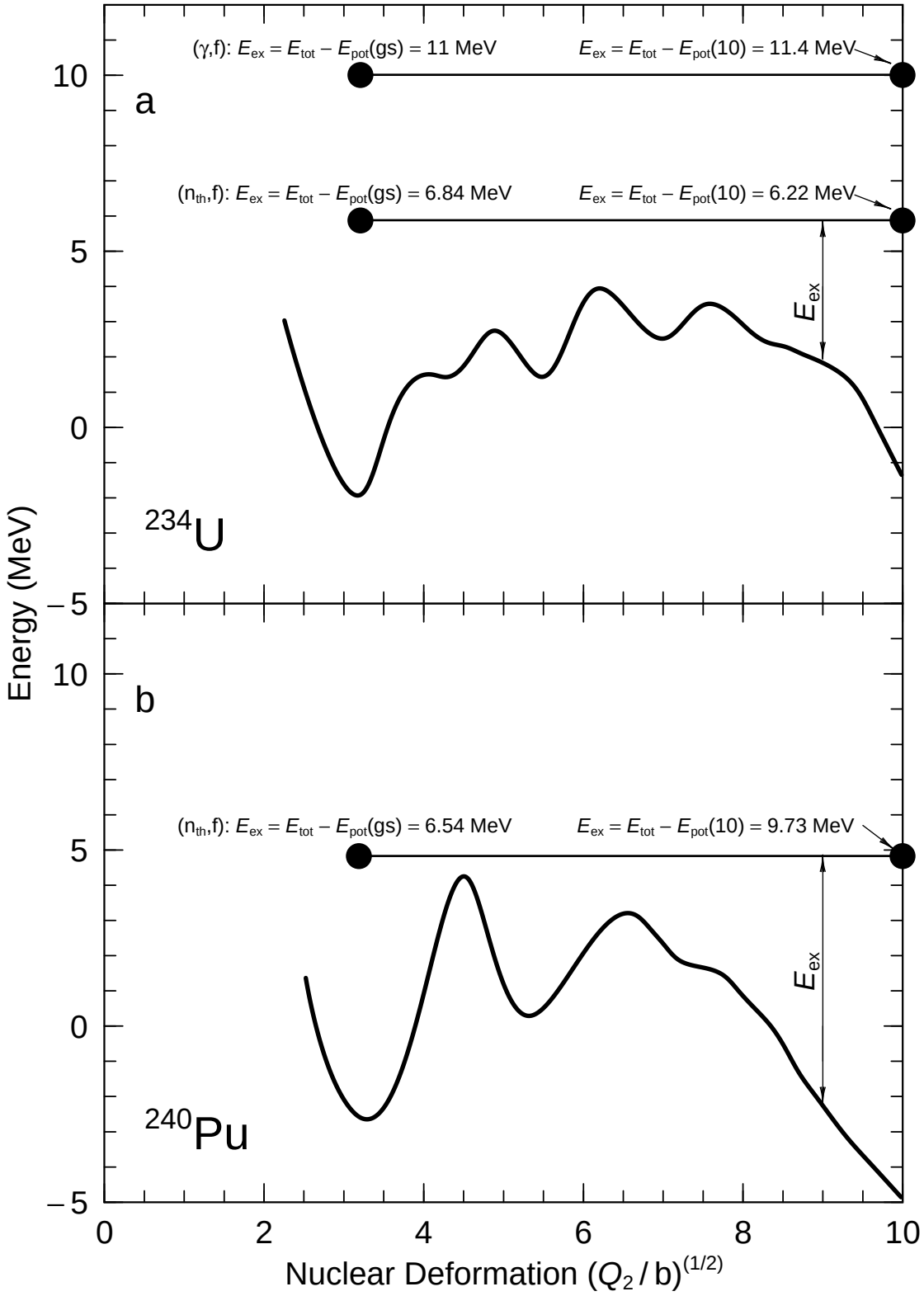

Theory
Experiment
234U
(n,f), E*=6.84
Δ = 1.0
CS = 1.5
236U
(n,f), E*=6.54
Δ = 1.0
CS = 1.5
238U
E*=7.4
Δ = 1.0
CS = 1.5
240U
E*=7.4
Δ = 1.0
CS = 1.5
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

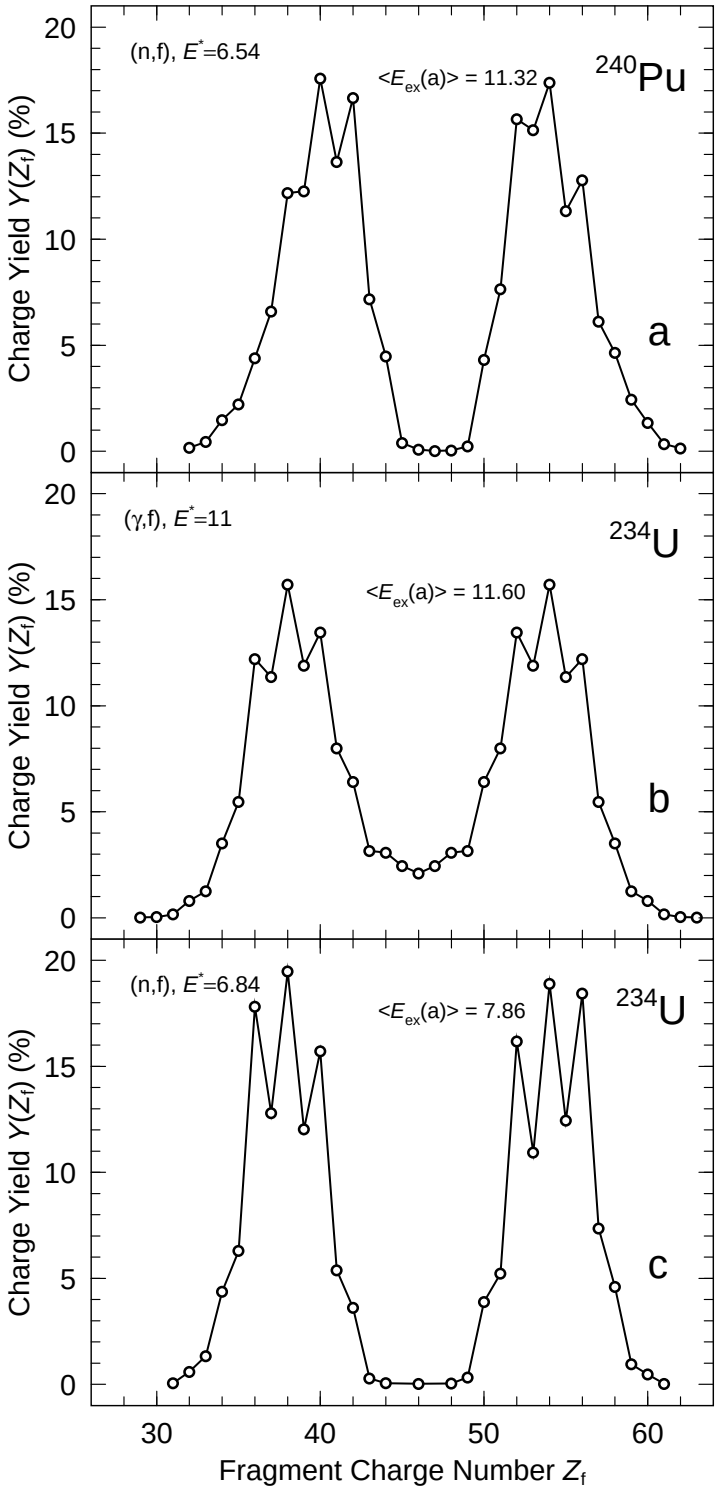

Theory
Experiment
234U
(n,f), E*=6.84
Δ = 1.0
CS = 1.5
236U
(n,f), E*=6.54
Δ = 1.0
CS = 1.5
238U
E*=7.4
Δ = 1.0
CS = 1.5
240U
E*=7.4
Δ = 1.0
CS = 1.5
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

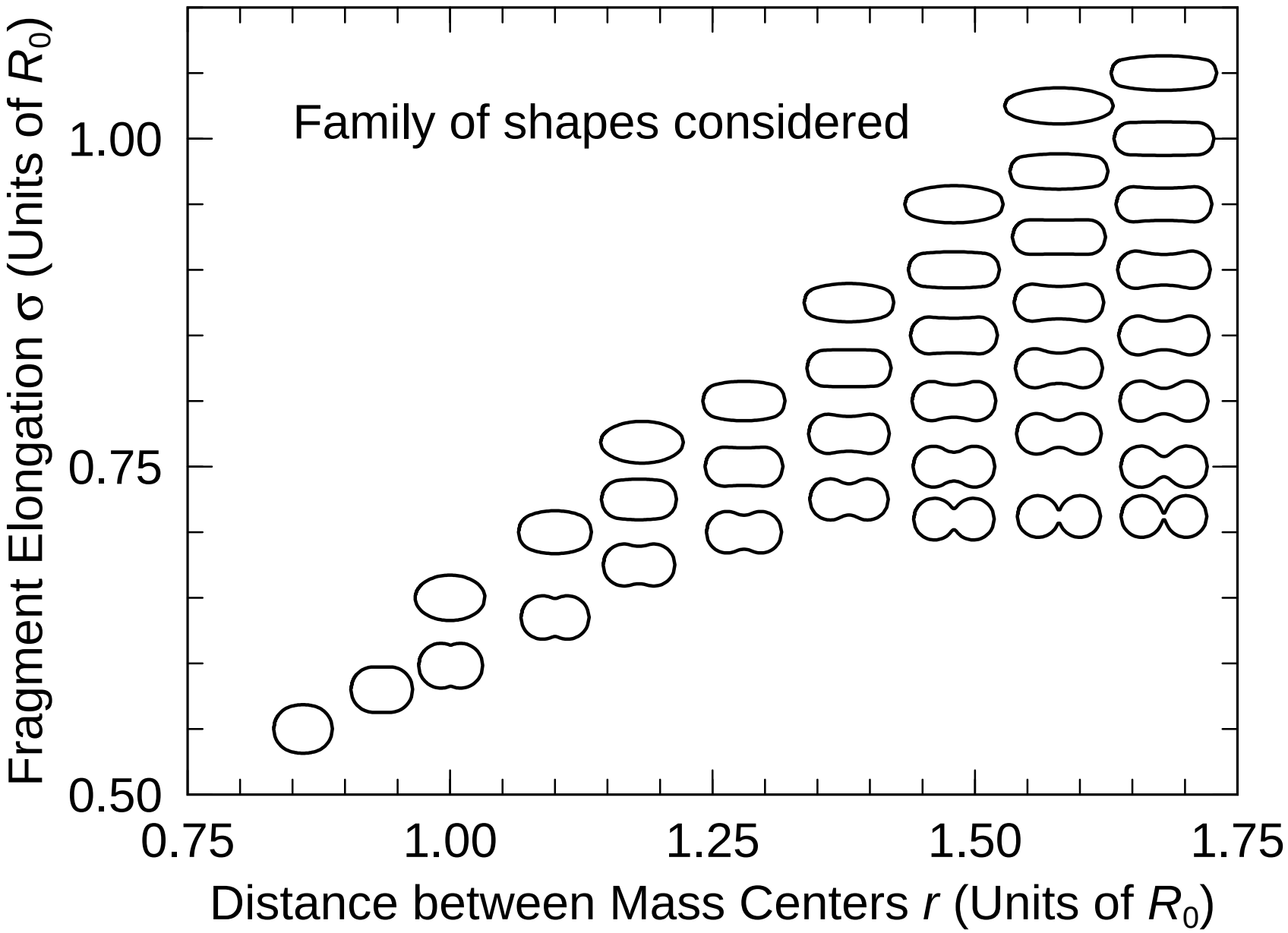

th. based on full Y(Z,N), sh. damp.
exp.
50k Tracks
C_S = 1.0
^{234}U
E^*=6.84 MeV
Δ = 1.0 MeV
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

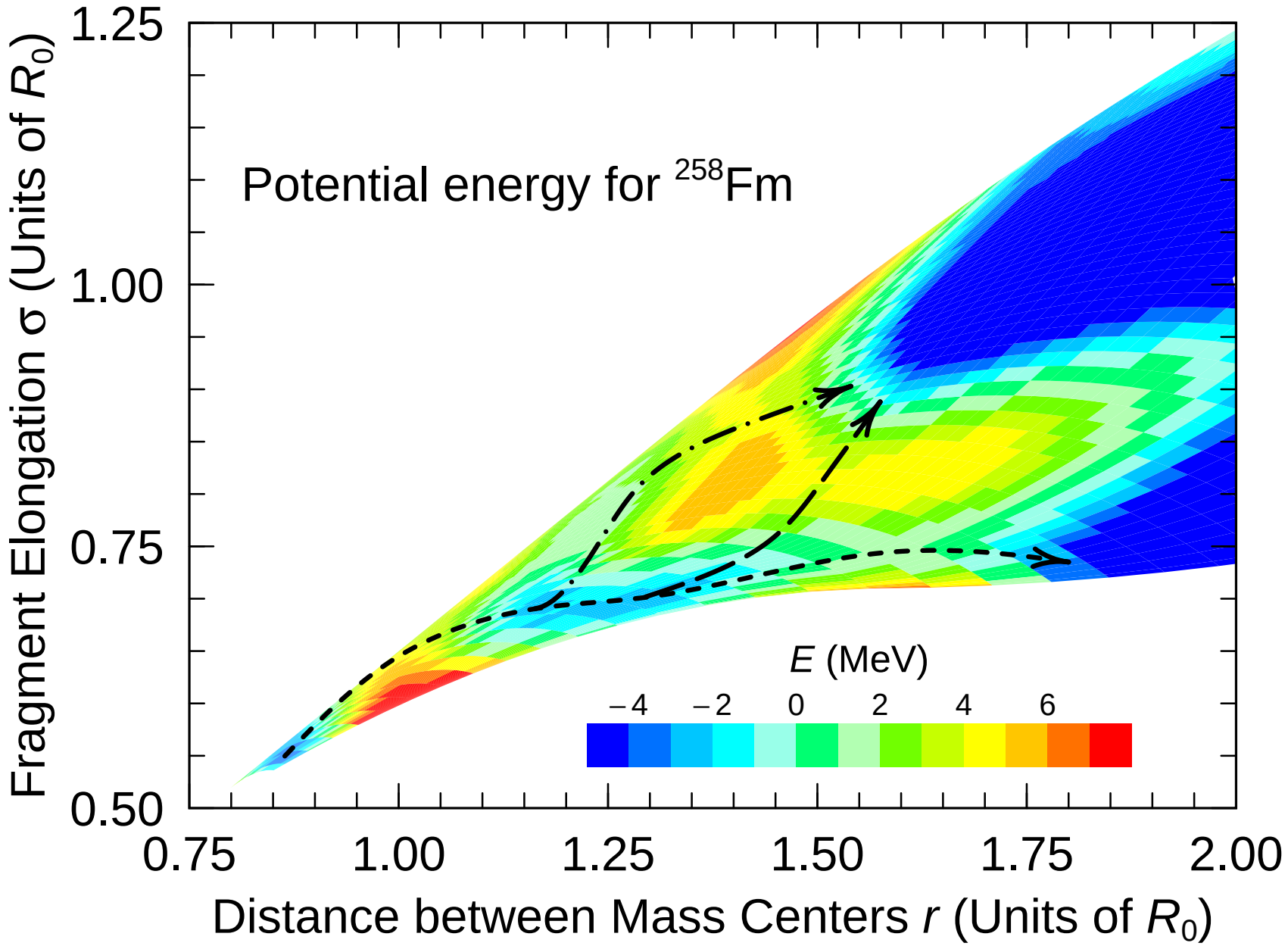

th. based on full Y(Z,N), sh. damp.
exp.
^{234}U
E^*=11.0 MeV
Δ = 1.0 MeV
50k Tracks
C_S = 1.0
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

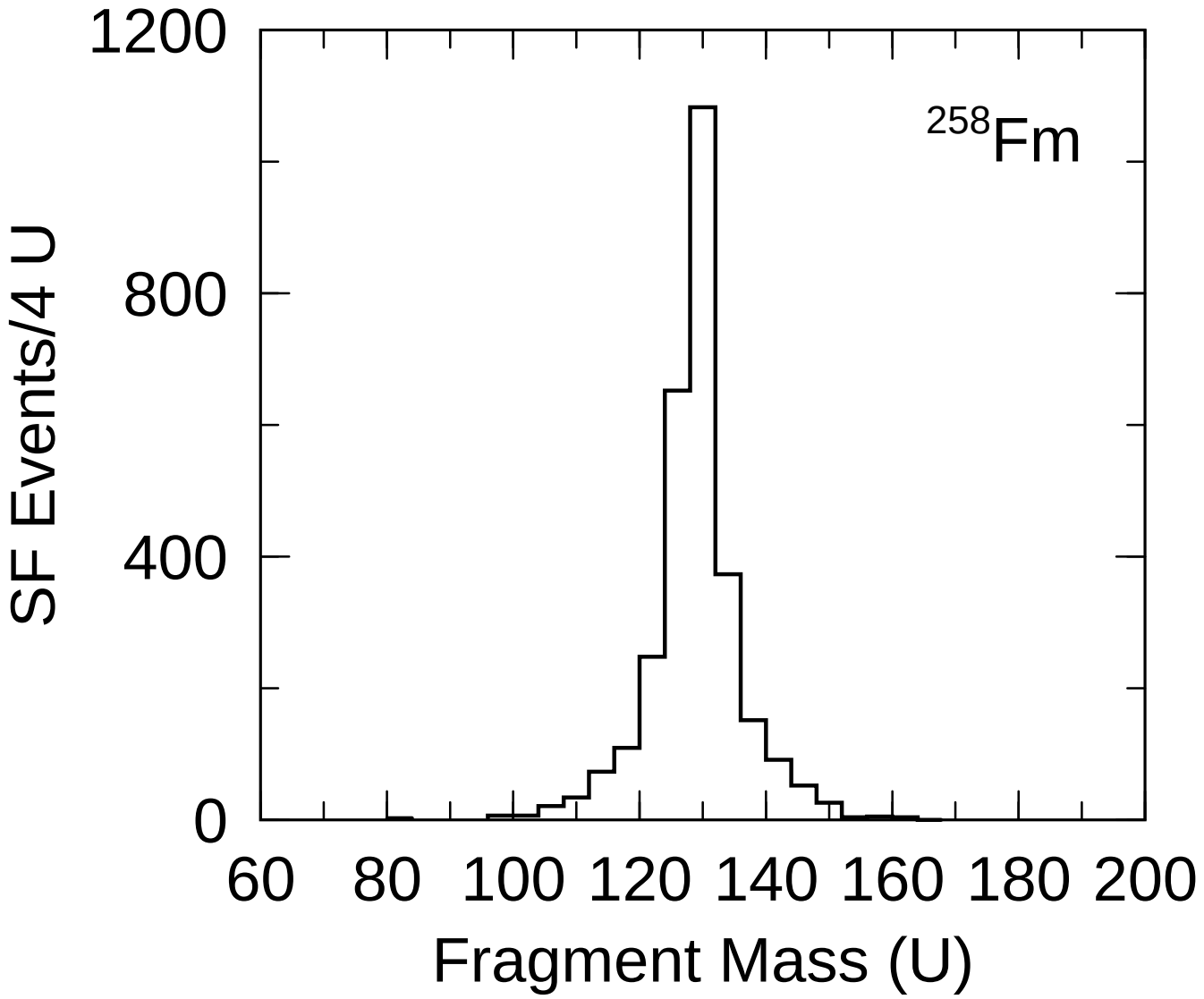

th. based on full Y(Z,N)
exp.
240Pu
E*=7.5 MeV
Δ = 1.0 MeV
20k Tracks
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

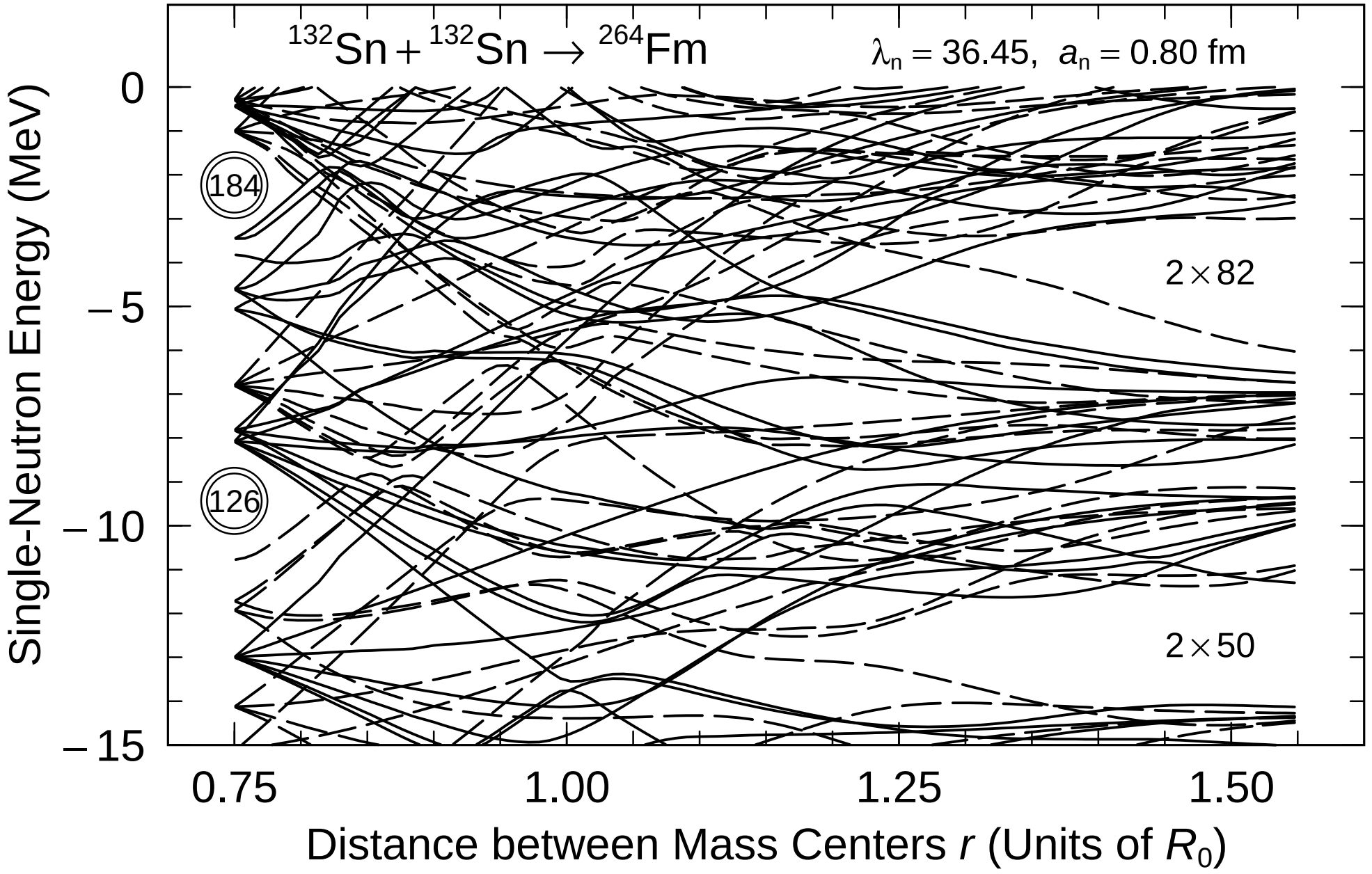

(γ,f): $E_{ex} = E_{tot} - E_{pot}$(gs) = 11 MeV
$E_{ex} = E_{tot} - E_{pot}$(10) = 11.4 MeV
a
(n_{th},f): $E_{ex} = E_{tot} - E_{pot}$(gs) = 6.84 MeV
$E_{ex} = E_{tot} - E_{pot}$(10) = 6.22 MeV
E_{ex}
^{234}U
b
(n_{th},f): $E_{ex} = E_{tot} - E_{pot}$(gs) = 6.54 MeV
$E_{ex} = E_{tot} - E_{pot}$(10) = 9.73 MeV
E_{ex}
^{240}Pu
Energy (MeV)
10
5
0
−5
0
2
4
6
8
10
Nuclear Deformation $(Q_2 / b)^{(1/2)}$

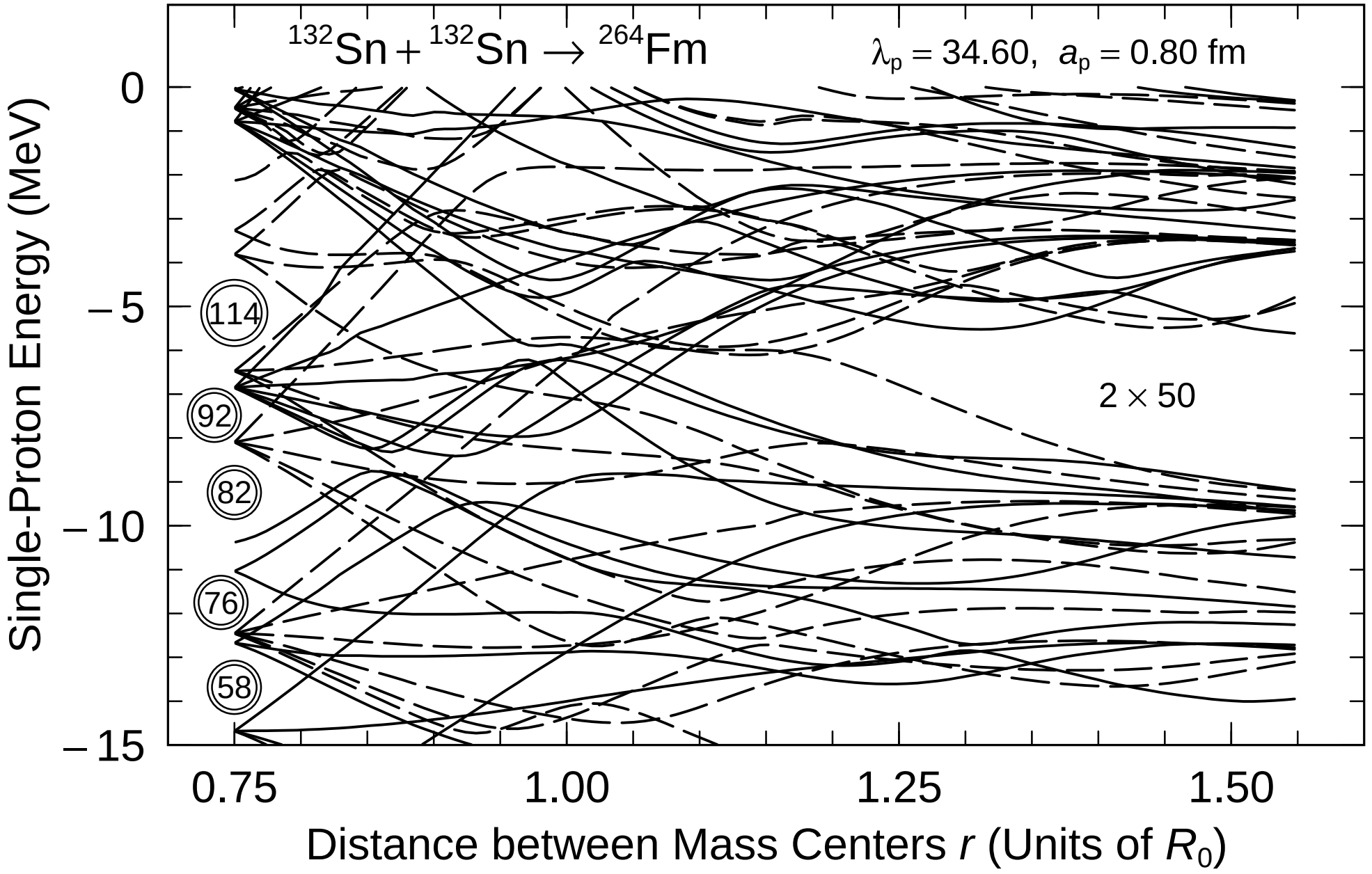

(n,f), E^*=6.54
<E_{ex}(a)> = 11.32
^{240}Pu
a
(γ,f), E^*=11
^{234}U
<E_{ex}(a)> = 11.60
b
(n,f), E^*=6.84
<E_{ex}(a)> = 7.86
^{234}U
c
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
30
40
50
60

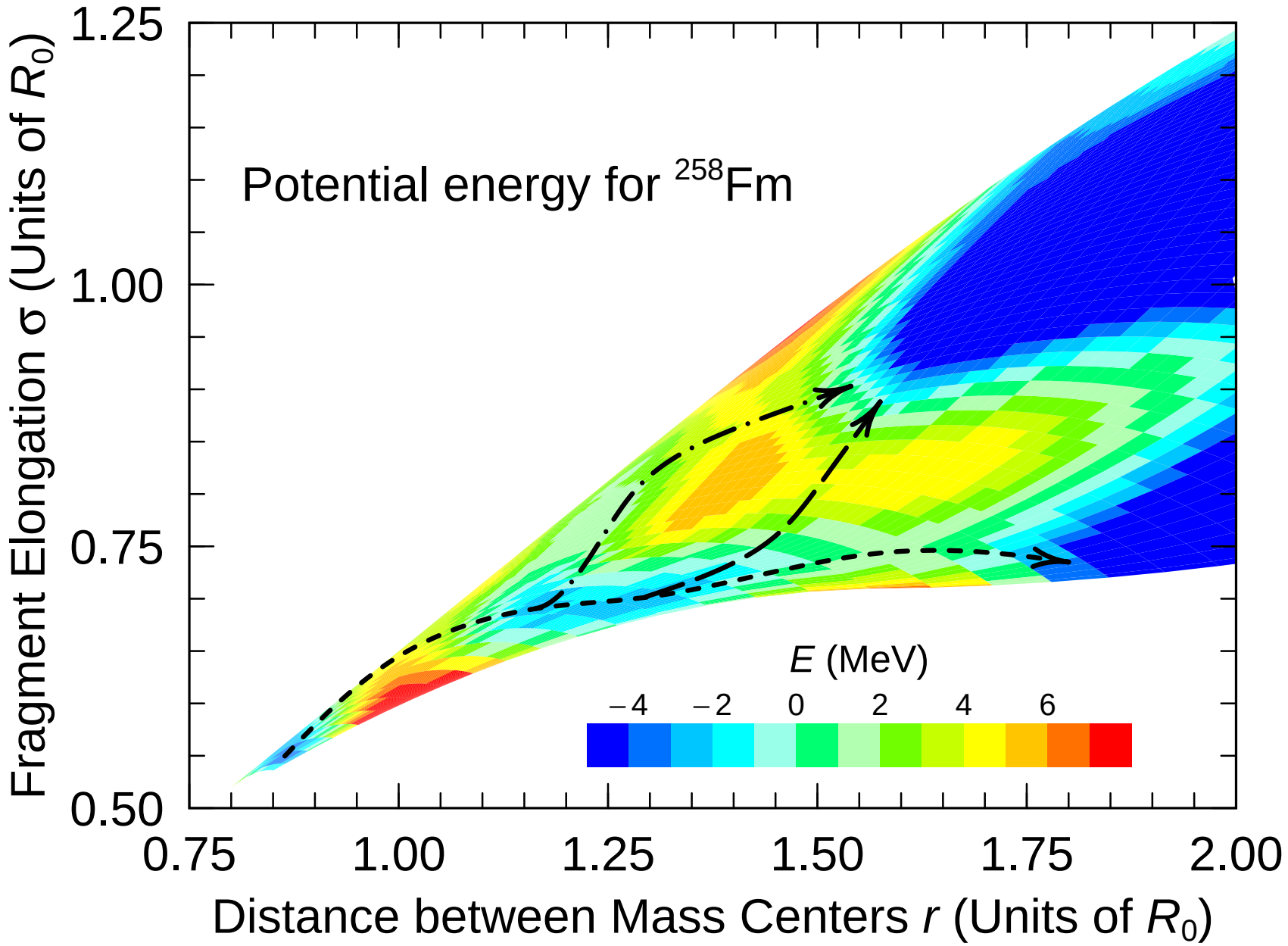

Family of shapes considered
Fragment Elongation σ (Units of R_0)
1.00
0.75
0.50
0.75
1.00
1.25
1.50
1.75
Distance between Mass Centers r (Units of R_0)

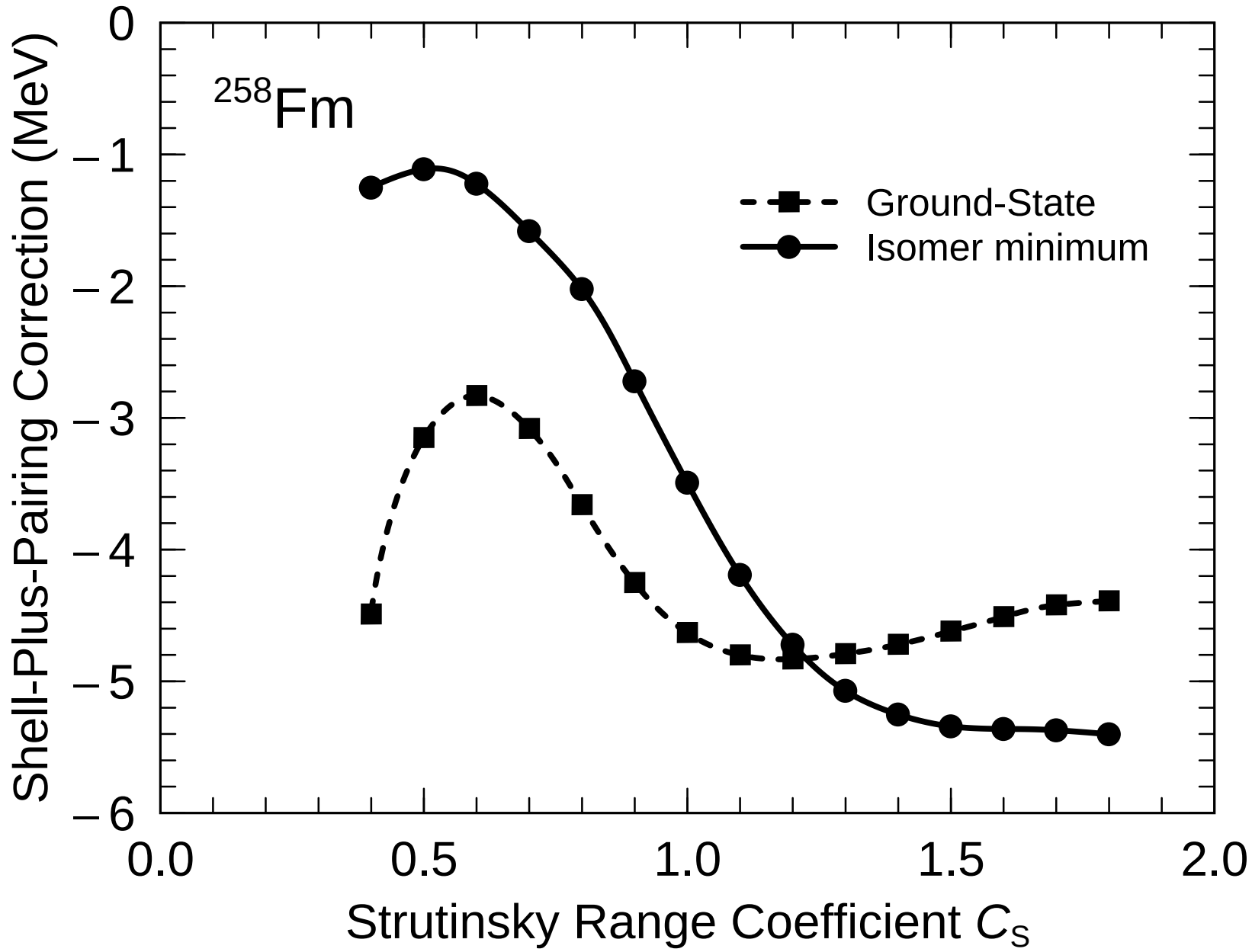

Potential energy for ^{258}Fm
Fragment Elongation σ (Units of R_0)
1.25
1.00
0.75
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Distance between Mass Centers r (Units of R_0)
E (MeV)
−4
−2
0
2
4
6

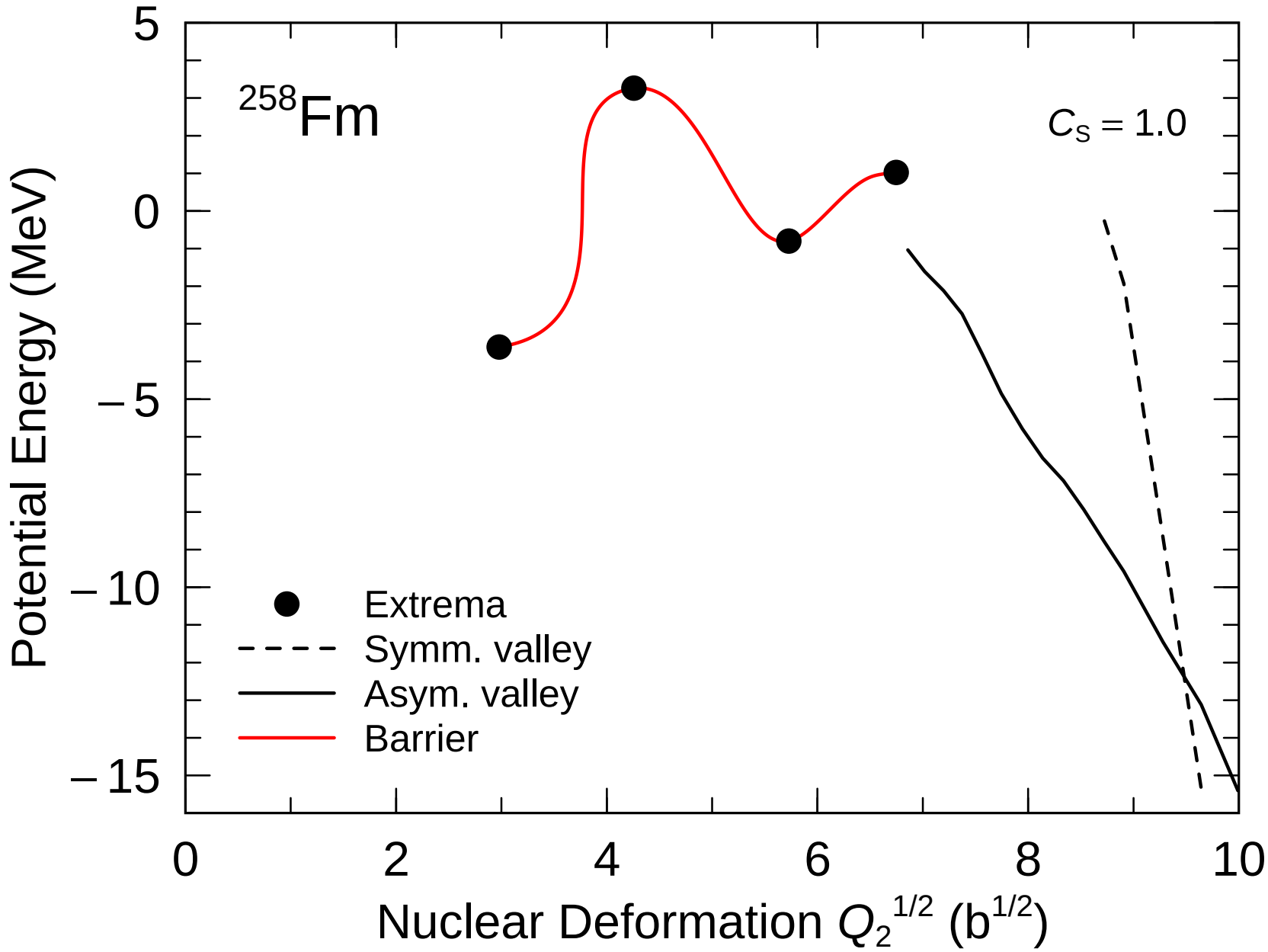

1200
800
400
0
SF Events/4 U
^{258}Fm
60
80
100
120
140
160
180
200
Fragment Mass (U)

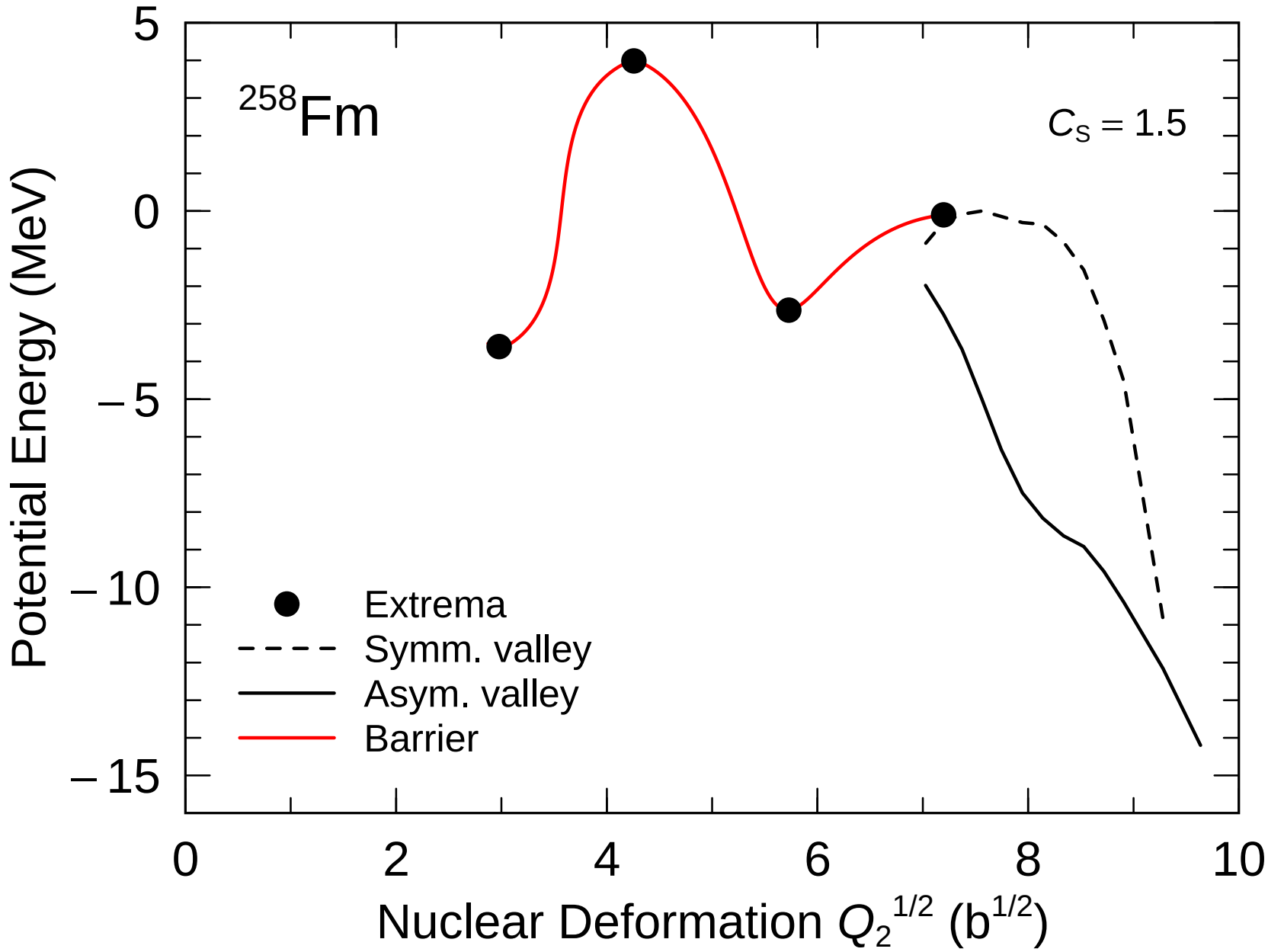

^{132}Sn + ^{132}Sn → ^{264}Fm
$\lambda_n = 36.45$, $a_n = 0.80$ fm
184
126
2×82
2×50
0
−5
−10
−15
Single-Neutron Energy (MeV)
0.75
1.00
1.25
1.50
Distance between Mass Centers r (Units of R_0)

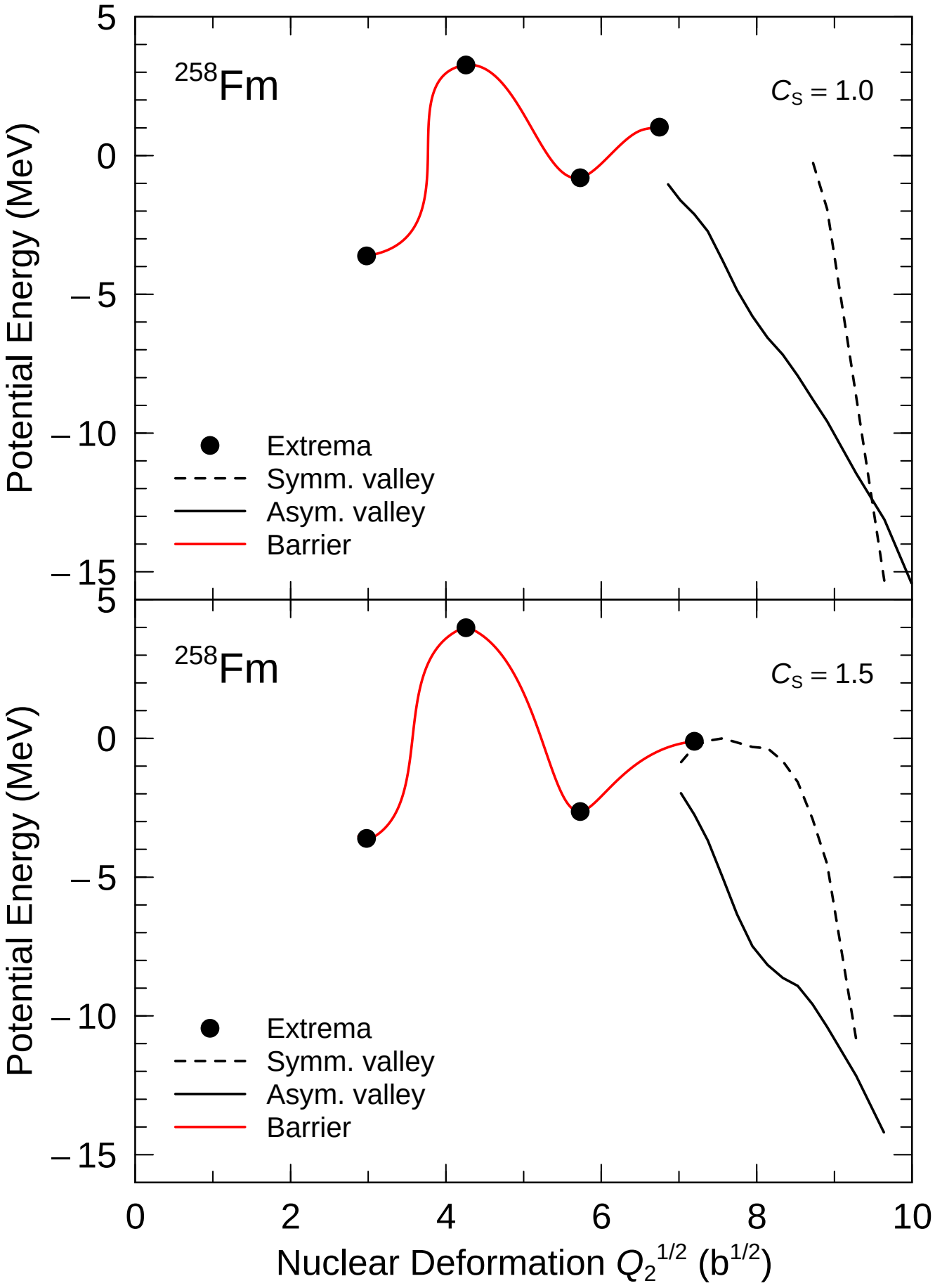

^{132}Sn + ^{132}Sn → ^{264}Fm
$\lambda_p = 34.60$, $a_p = 0.80$ fm
2 × 50
114
92
82
76
58
0
– 5
– 10
– 15
0.75
1.00
1.25
1.50
Single-Proton Energy (MeV)
Distance between Mass Centers r (Units of R_0)

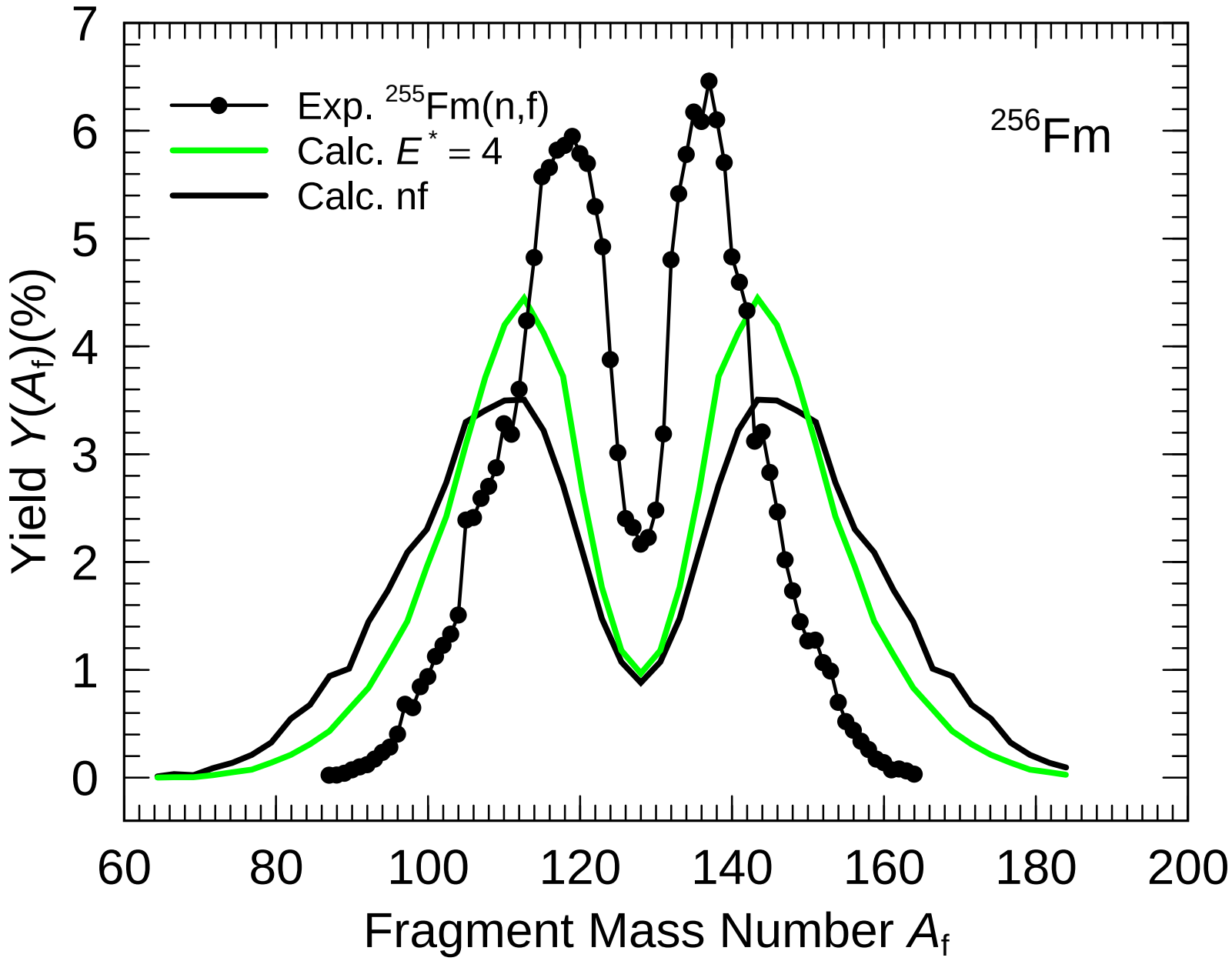

Potential energy for ^{258}Fm
Fragment Elongation σ (Units of R_0)
1.25
1.00
0.75
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Distance between Mass Centers r (Units of R_0)
E (MeV)
−4
−2
0
2
4
6

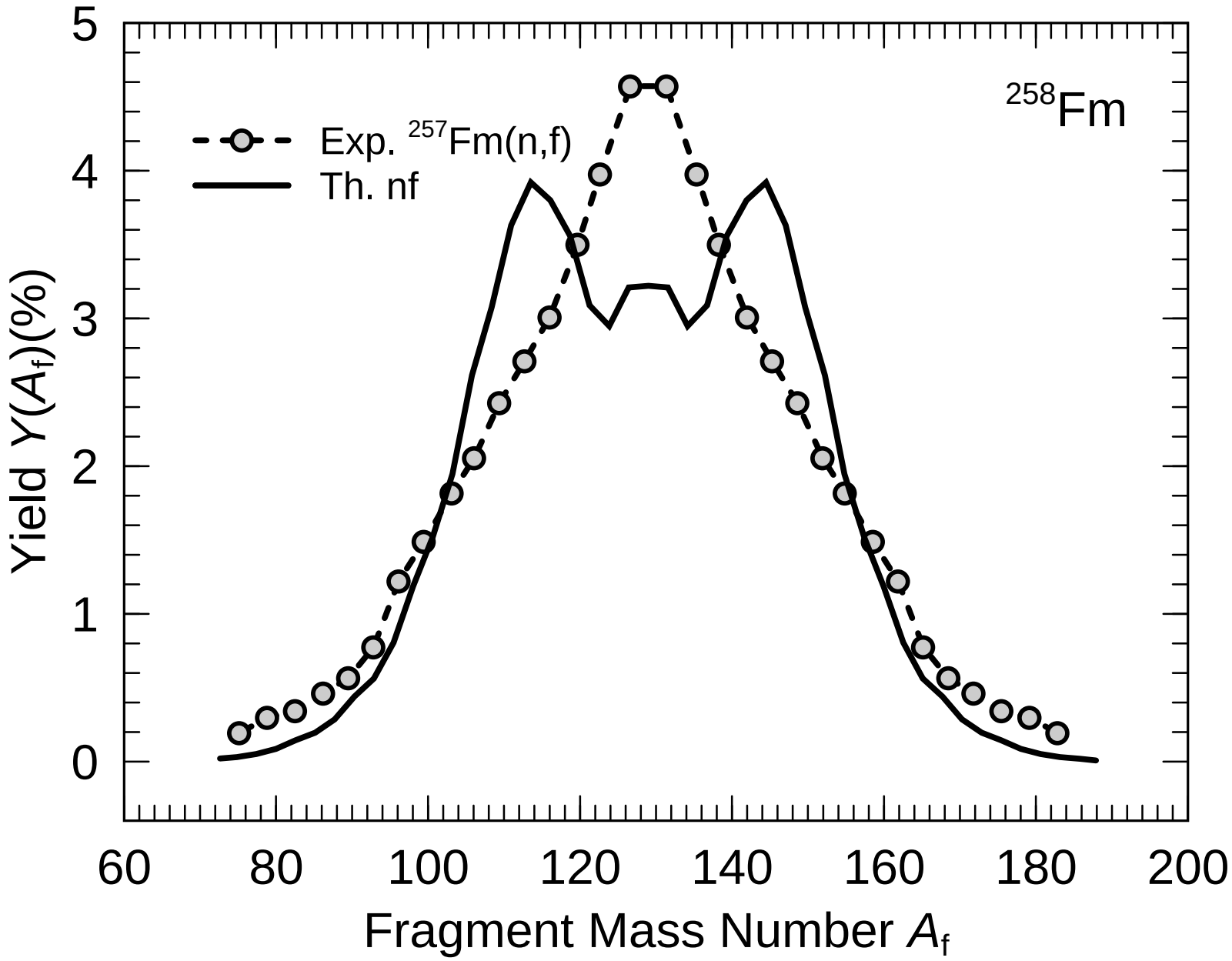

^{258}Fm
Ground-State
Isomer minimum
Shell-Plus-Pairing Correction (MeV)
0
−1
−2
−3
−4
−5
−6
0.0
0.5
1.0
1.5
2.0
Strutinsky Range Coefficient C_S

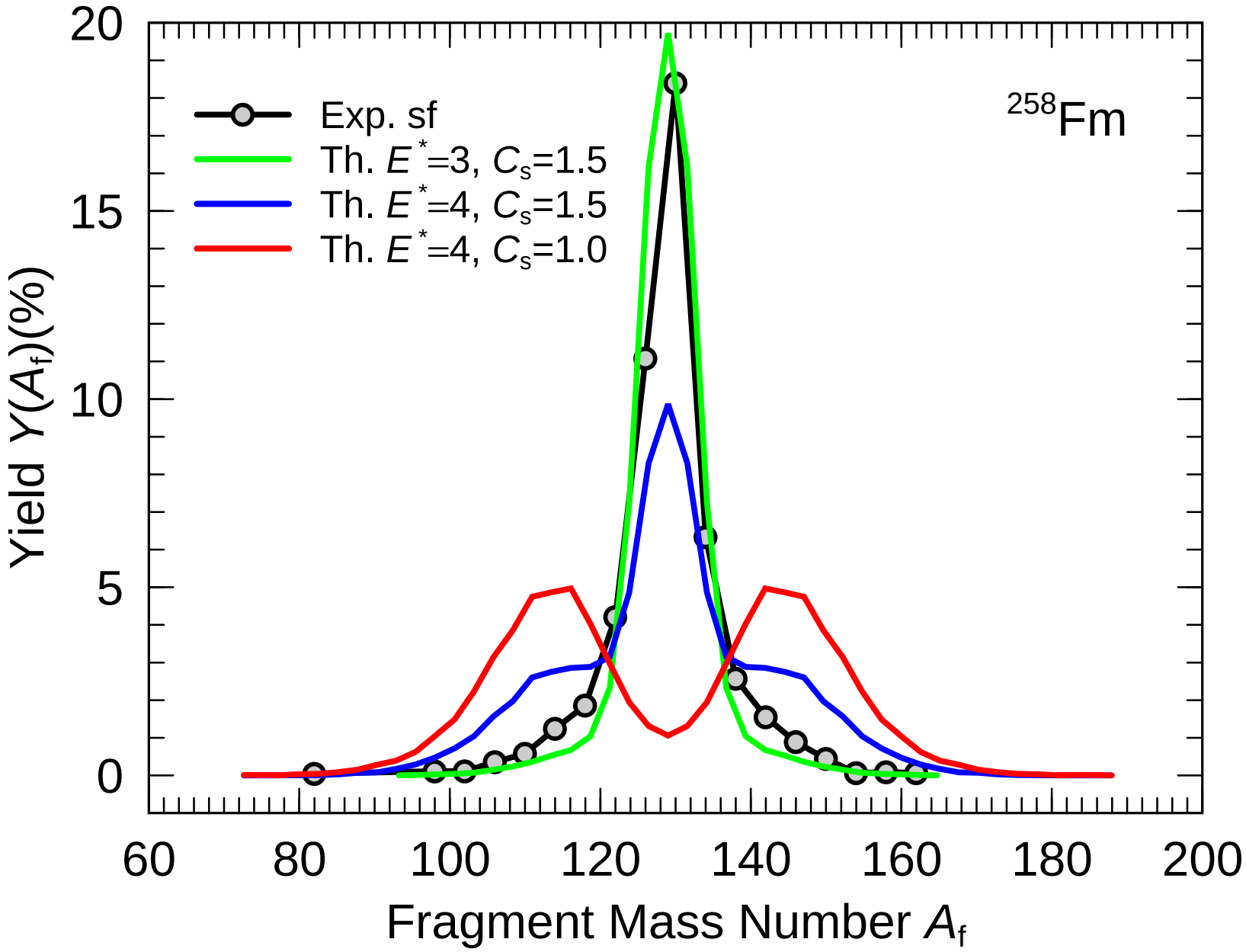

^{258}Fm
C_S = 1.0
Potential Energy (MeV)
5
0
– 5
– 10
– 15
0
2
4
6
8
10
Nuclear Deformation $Q_2^{1/2}$ (b$^{1/2}$)
Extrema
Symm. valley
Asym. valley
Barrier


^{258}Fm
C_S = 1.5
Potential Energy (MeV)
5
0
– 5
– 10
– 15
0
2
4
6
8
10
Nuclear Deformation $Q_2^{1/2}$ (b$^{1/2}$)
Extrema
Symm. valley
Asym. valley
Barrier


^{258}Fm
$C_S = 1.0$
Extrema
Symm. valley
Asym. valley
Barrier
^{258}Fm
$C_S = 1.5$
Extrema
Symm. valley
Asym. valley
Barrier
Potential Energy (MeV)
Potential Energy (MeV)
5
0
−5
−10
−15
0
2
4
6
8
10
Nuclear Deformation $Q_2^{1/2}$ (b$^{1/2}$)


Exp. ^{255}Fm(n,f)
Calc. $E^* = 4$
Calc. nf
^{256}Fm
Yield $Y(A_f)$(%)
Fragment Mass Number A_f
0
1
2
3
4
5
6
7
60
80
100
120
140
160
180
200


Exp. 257Fm(n,f)
Th. nf
258Fm
Yield Y(Af)(%)
Fragment Mass Number Af
0
1
2
3
4
5
60
80
100
120
140
160
180
200


Exp. sf
Th. E^*=3, C_s=1.5
Th. E^*=4, C_s=1.5
Th. E^*=4, C_s=1.0
^{258}Fm
Yield $Y(A_f)$(%)
Fragment Mass Number A_f
0
5
10
15
20
60
80
100
120
140
160
180
200