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Fission Barriers and Fission-Fragment Yields in the Region $170 < A \leq 330$

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Collaborators on this and other projects:
W. D. Myers, J. Randrup(LBL), 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) . . .).

More details about fission (PRC 79 064304, PRC 84 034613, PRC 88 064606), other projects (beta-decay,masses), 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/

Potential Energy of Deformation

We use the macroscopic-microscopic method introduced by Swiatecki and Strutinsky:

$$E_{\rm pot}({\rm shape}) = E_{\rm macr}({\rm shape}) + E_{\rm micr}({\rm shape}) \quad (1)$$

The macroscopic term is calculated in a liquid-drop type model (for a specific deformed shape).

The microscopic correction is determined in the following steps

1. A shape is prescribed
2. A single-particle potential with this shape is generated. A spin-orbit term is included.
3. The Schrödinger equation is solved for this deformed potential and single-particle levels and wave-functions are obtained
4. The shell correction is calculated by use of Strutinsky's method.
5. The pairing correction is calculated in the BCS or Lipkin-Nogami method.

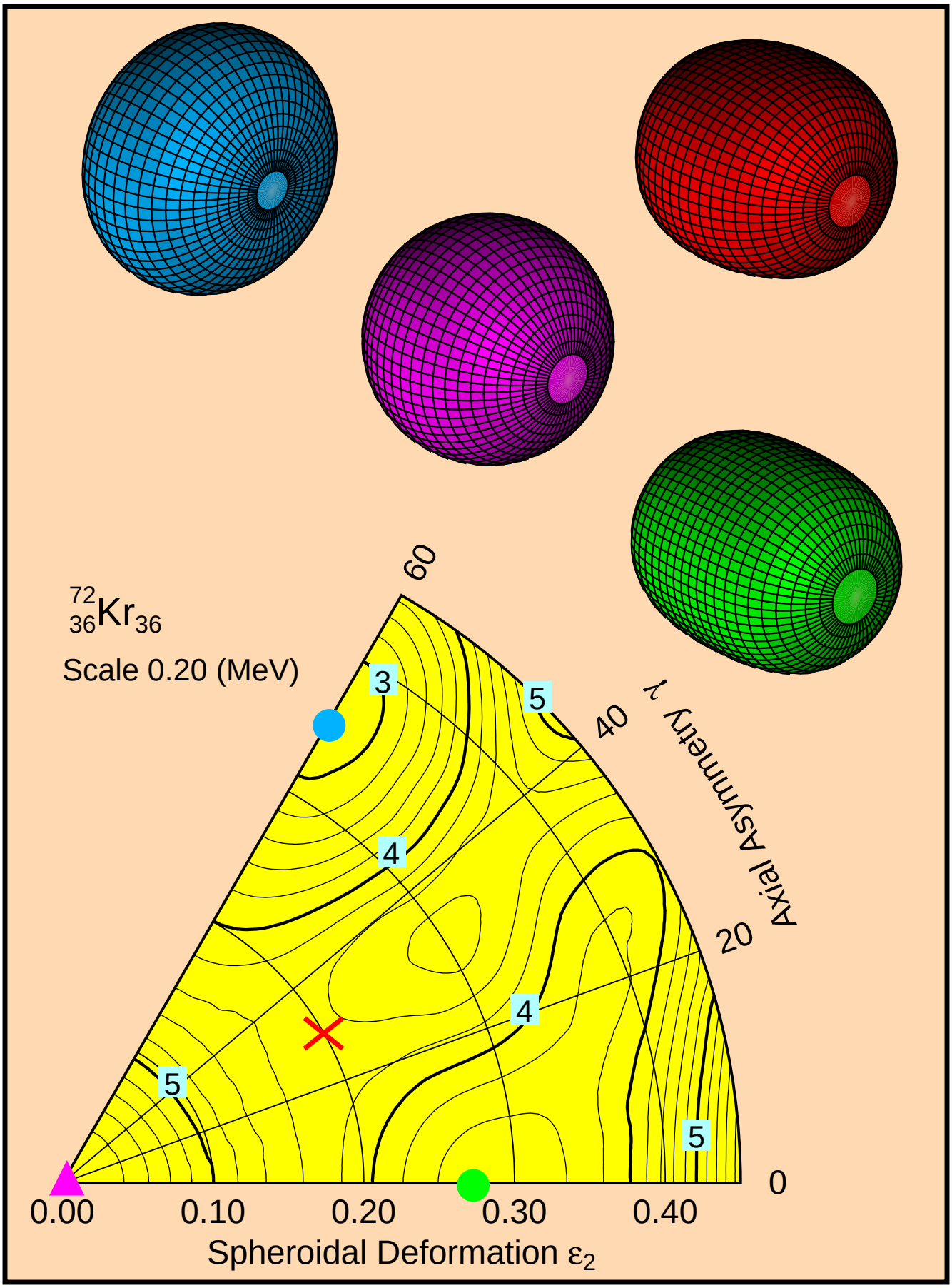
Shape Parameterizations

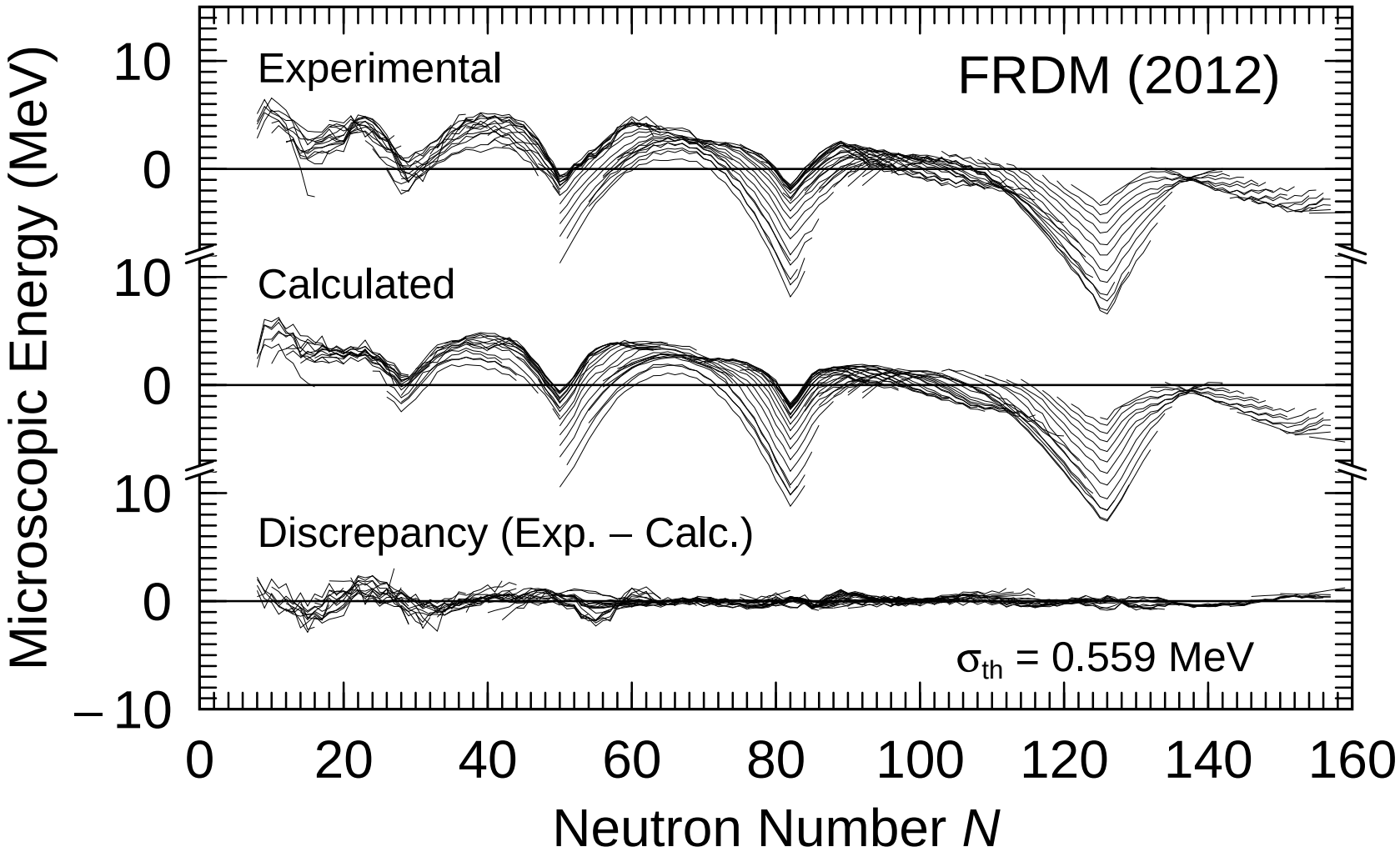
For small distortions we use multipole expansions, for example the β parameterization:

$$r(\theta,\phi) = R_0(1 + \sum_{l=1}^{\infty}\sum_{m=-l}^{l}\beta_{lm}Y_l^m)$$

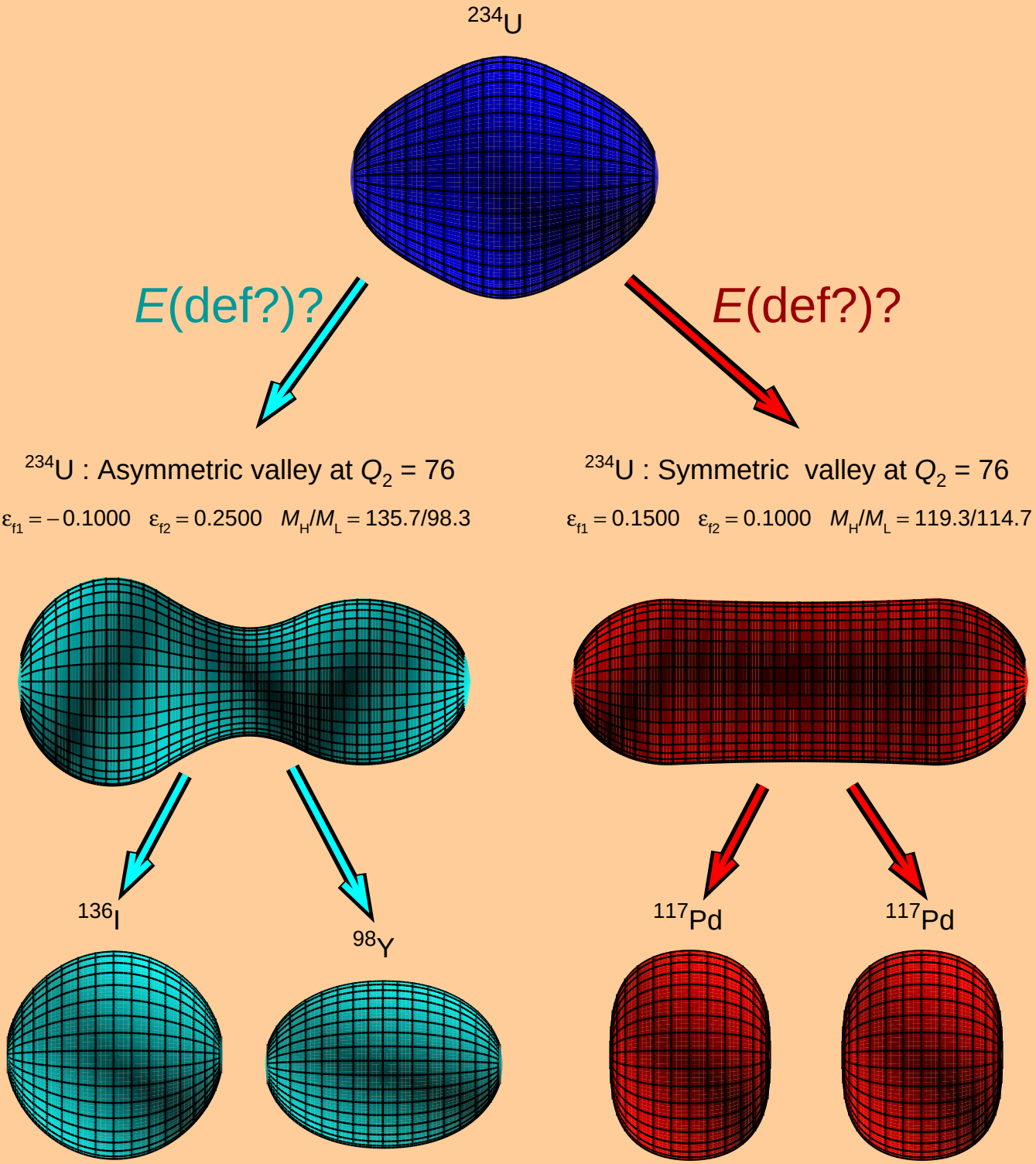
For large deformations near the outer saddle in the actinide region or beyond we use the three-quadratic-surface parameterization:

$$\rho(z)^2 = \begin{cases} {a_1}^2 - \dfrac{{a_1}^2}{{c_1}^2}(z-l_1)^2 \quad , & l_1 - c_1 \le z \le z_1 \\ {a_2}^2 - \dfrac{{a_2}^2}{{c_2}^2}(z-l_2)^2 \quad , & z_2 \le z \le l_2 + c_2 \\ {a_3}^2 - \dfrac{{a_3}^2}{{c_3}^2}(z-l_3)^2 \quad , & z_1 \le z \le z_2 \end{cases}$$

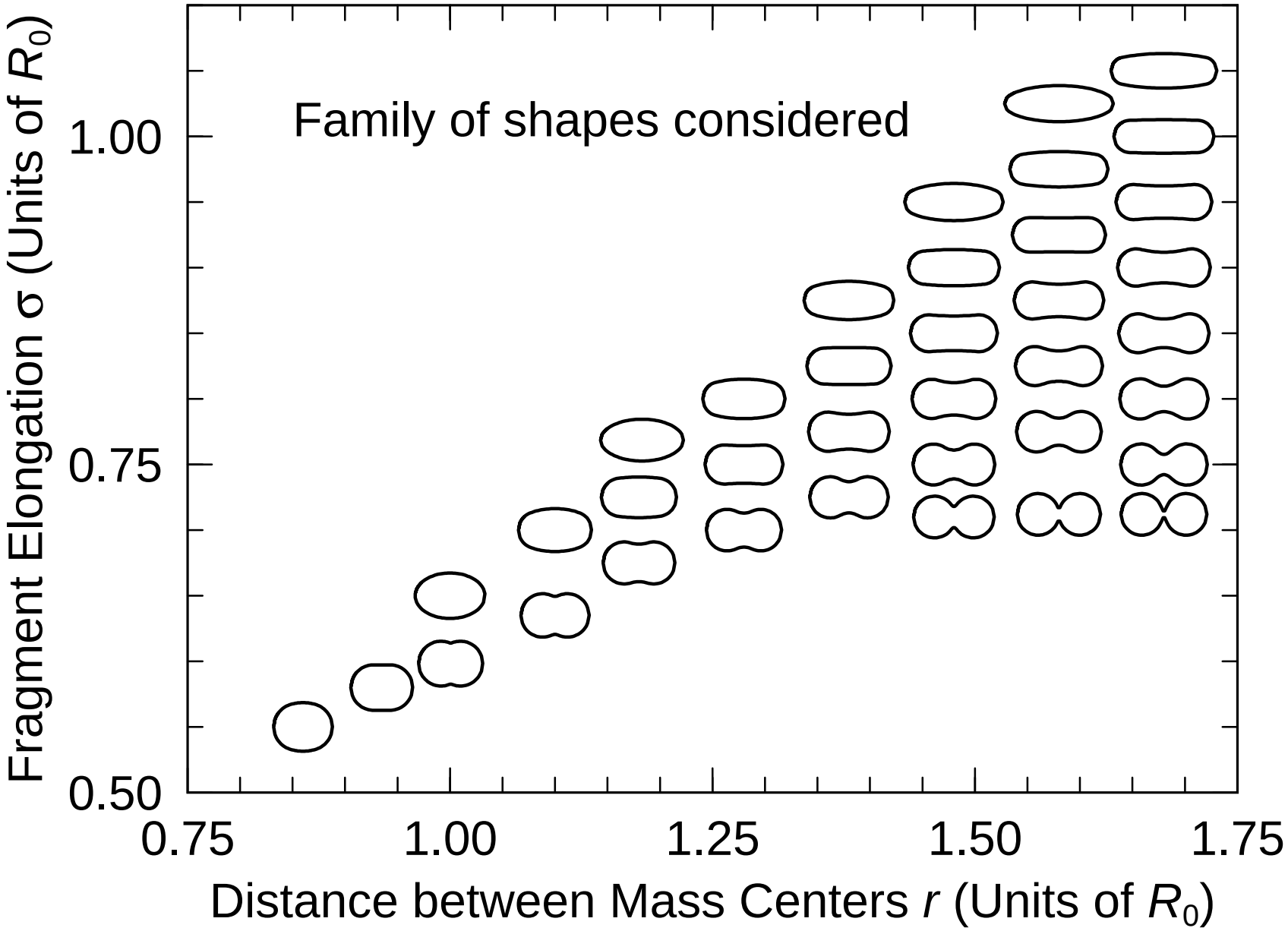

$^{72}_{36}Kr_{36}$
Scale 0.20 (MeV)
3
4
5
4
5
5
60
40
20
0
Axial Asymmetry γ
0.00
0.10
0.20
0.30
0.40
Spheroidal Deformation ε2


Experimental
FRDM (2012)
Calculated
Discrepancy (Exp. – Calc.)
σth = 0.559 MeV
Microscopic Energy (MeV)
10
0
10
0
10
0
– 10
0
20
40
60
80
100
120
140
160
Neutron Number N

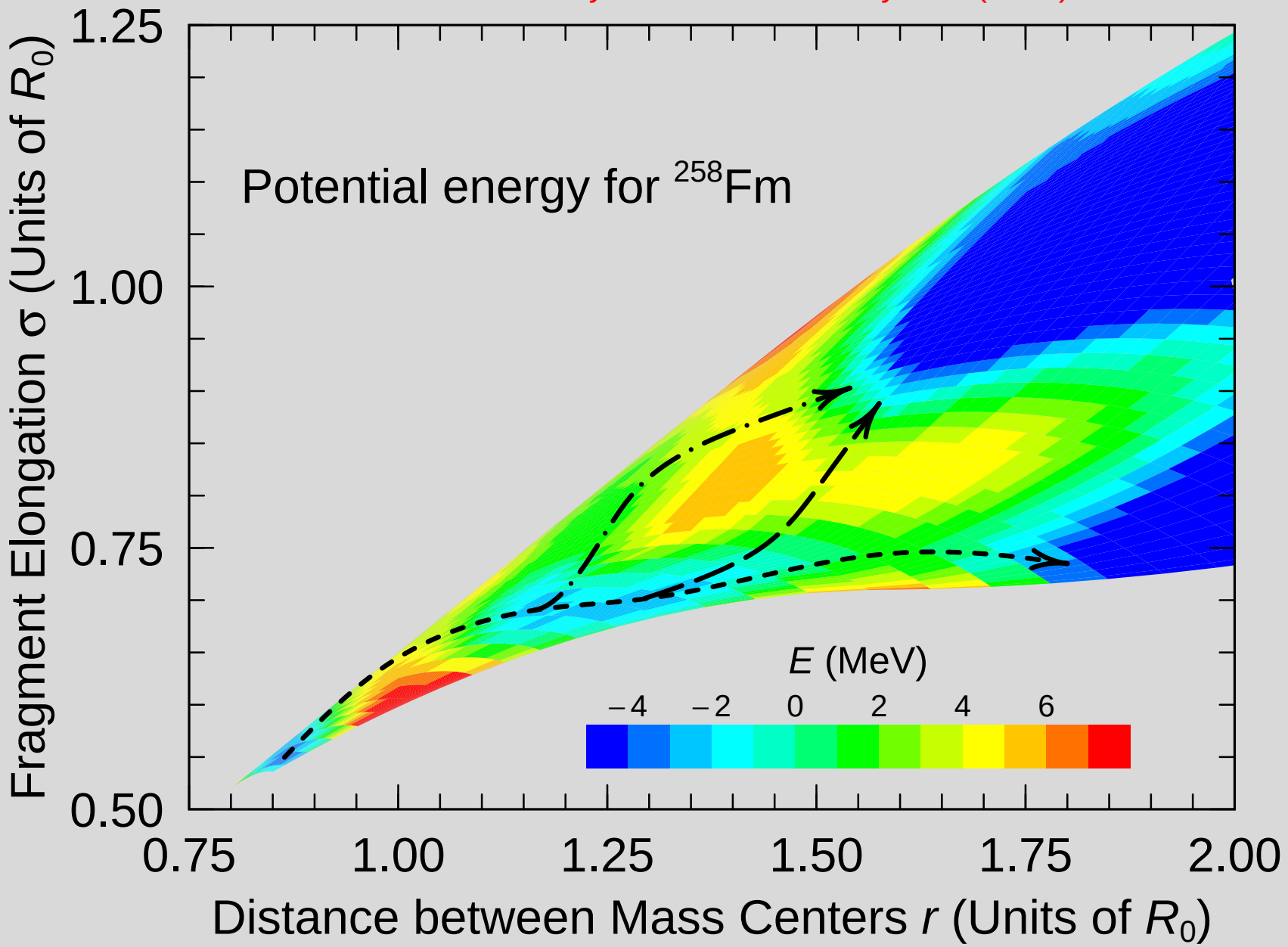
In fission, what are the shapes and related energies involved in the transition from a single ground-state shape to two separated fission fragments?



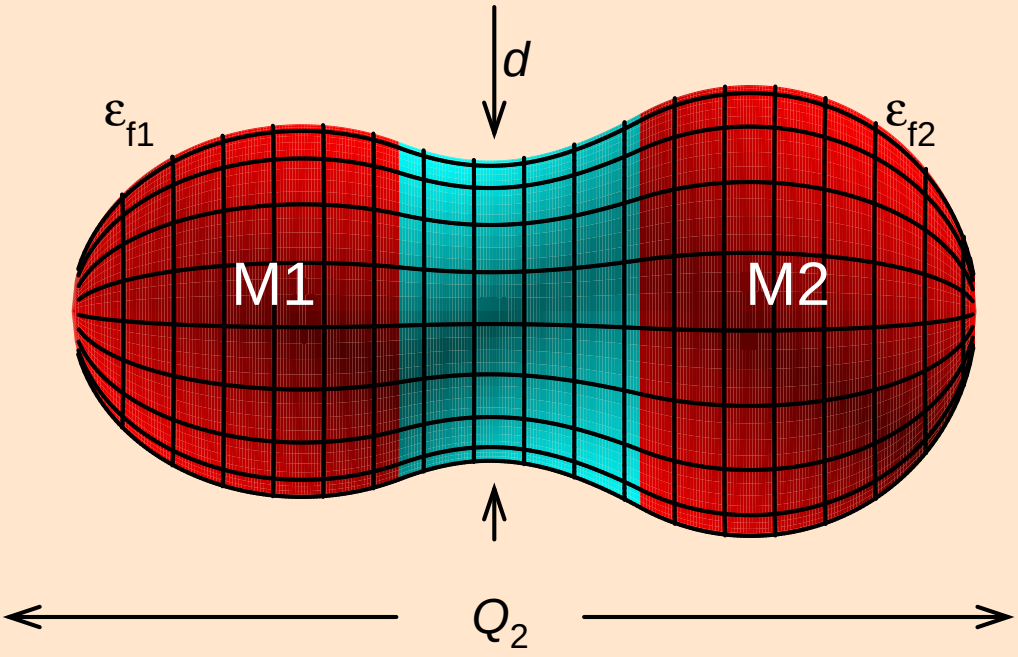
From: Nucl. Phys A469 (1987) 1



From: Journ. Phys. G: Nucl. Part. Phys. 20 (1994) 1681



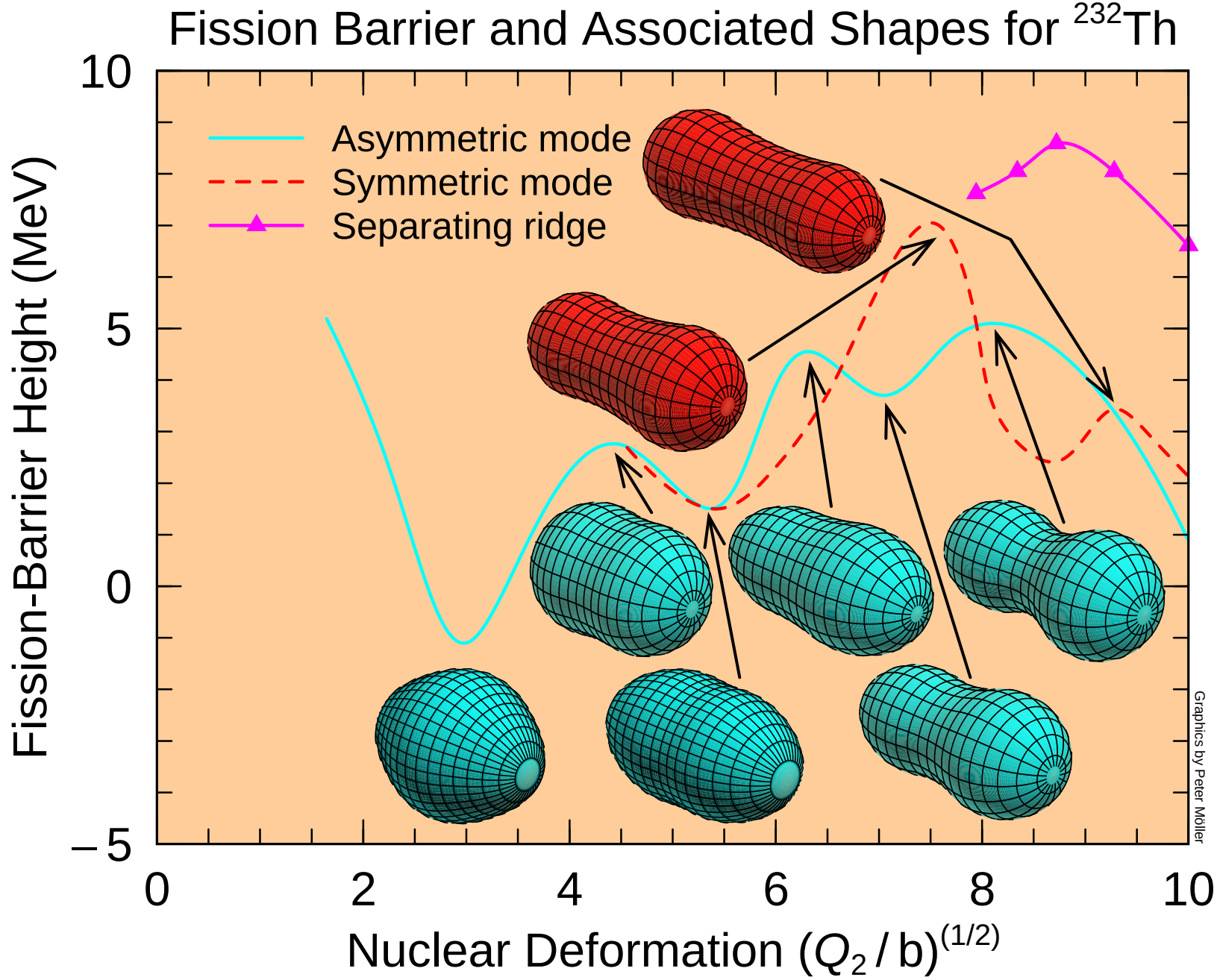
Five Essential Fission Shape Coordinates

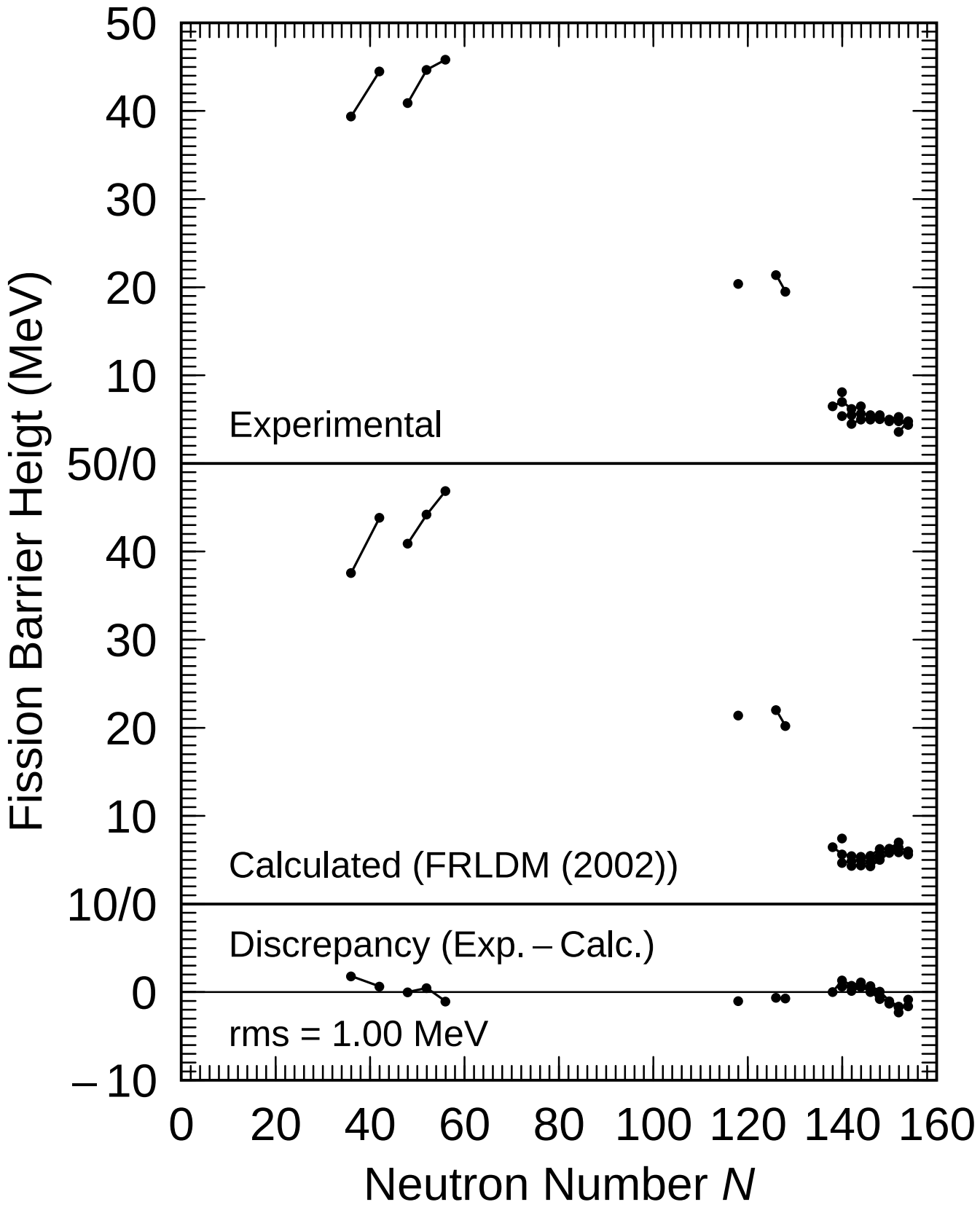


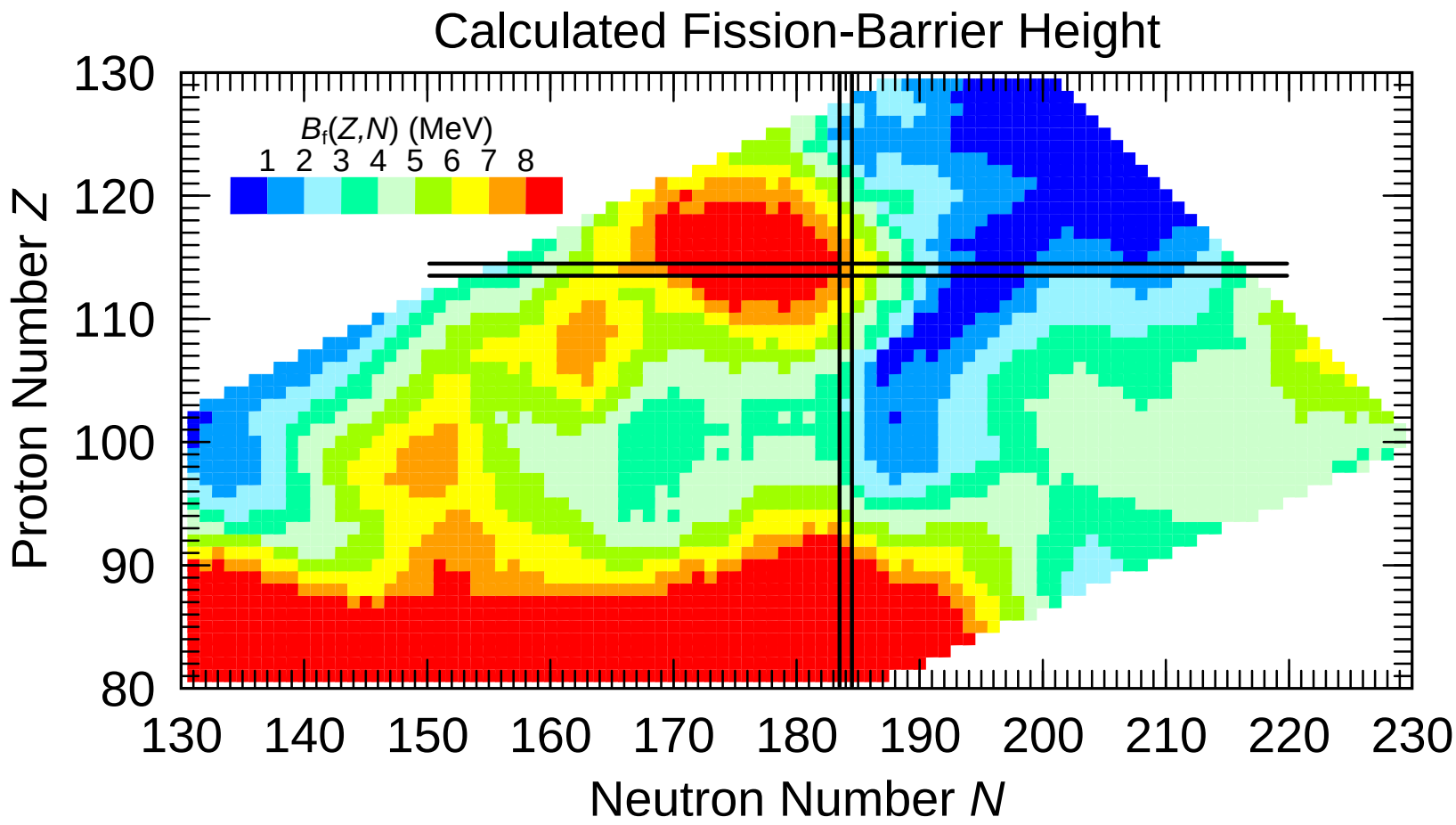
45	Q_2 ~	Elongation (fission direction)
⊗		
15	d ~	Neck
⊗		
15	ε_{f1} ~	Left fragment deformation
⊗		
15	ε_{f2} ~	Right fragment deformation
⊗		
35	α_g ~	(M1-M2)/(M1+M2) Mass asymmetry

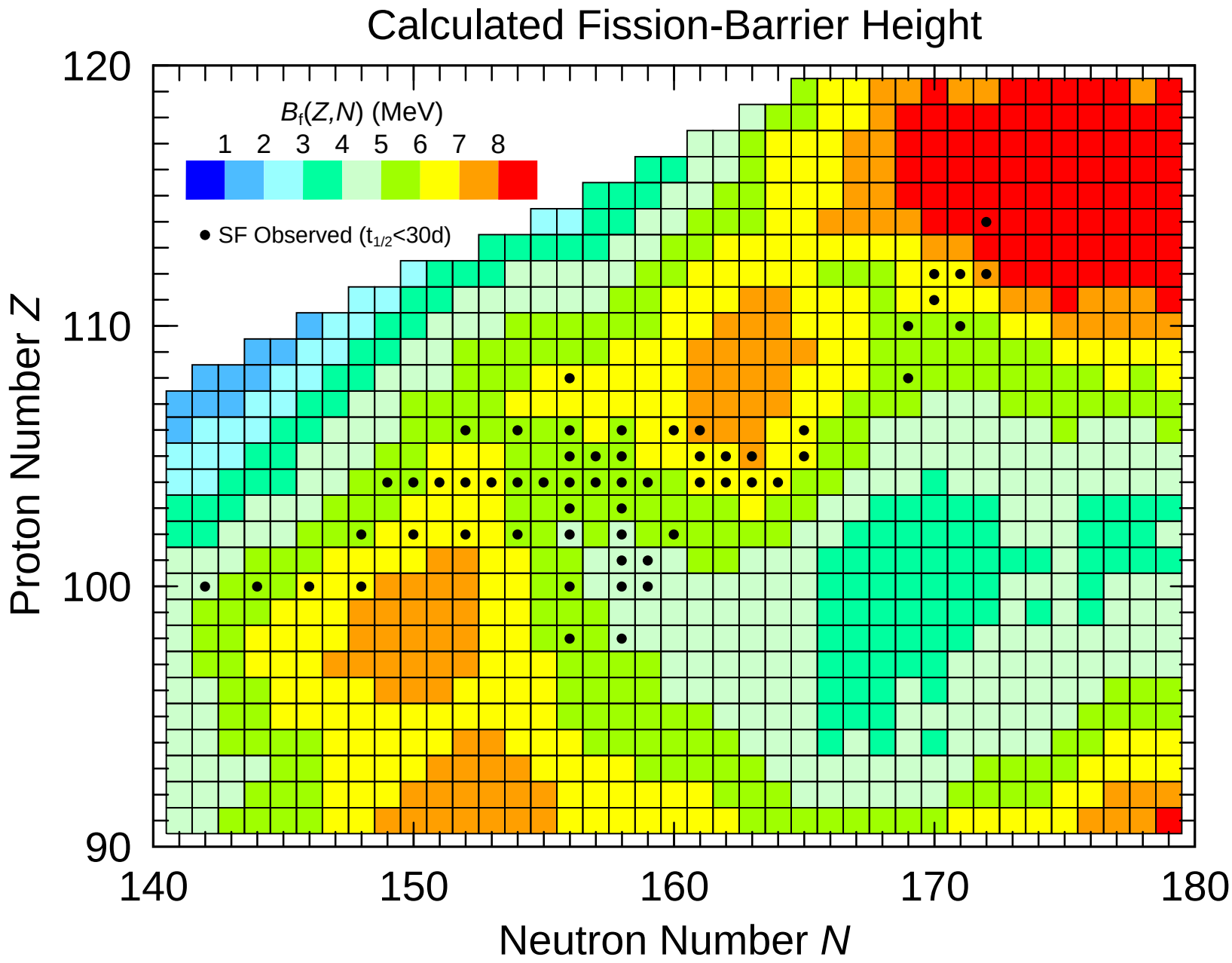
⇒ 5 315 625 grid points – 306 300 unphysical points

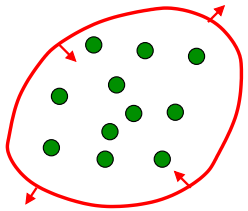
⇒ 5 009 325 physical grid points


Fission Barrier and Associated Shapes for ^{232}Th
Asymmetric mode
Symmetric mode
Separating ridge
Fission-Barrier Height (MeV)
10
5
0
−5
0
2
4
6
8
10
Nuclear Deformation $(Q_2 / \mathrm{b})^{(1/2)}$
Graphics by Peter Möller


Fission Barrier Heigt (MeV)
50
40
30
20
10
50/0
40
30
20
10
10/0
0
– 10
Experimental
Calculated (FRLDM (2002))
Discrepancy (Exp. – Calc.)
rms = 1.00 MeV
0
20
40
60
80
100
120
140
160
Neutron Number N


Calculated Fission-Barrier Height
$B_f(Z,N)$ (MeV)
1 2 3 4 5 6 7 8
Proton Number Z
130
120
110
100
90
80
130 140 150 160 170 180 190 200 210 220 230
Neutron Number N


Calculated Fission-Barrier Height
$B_f(Z,N)$ (MeV)
1 2 3 4 5 6 7 8
SF Observed ($t_{1/2}$<30d)
Proton Number Z
120
110
100
90
140
150
160
170
180
Neutron Number N



Brownian shape motion

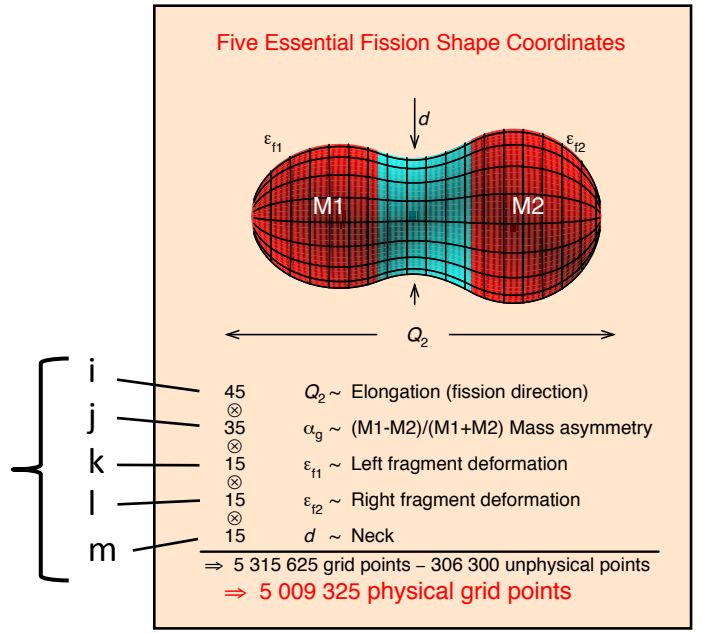
Nuclear deformation energy: $E_{def}(i,j,k,l,m)$

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

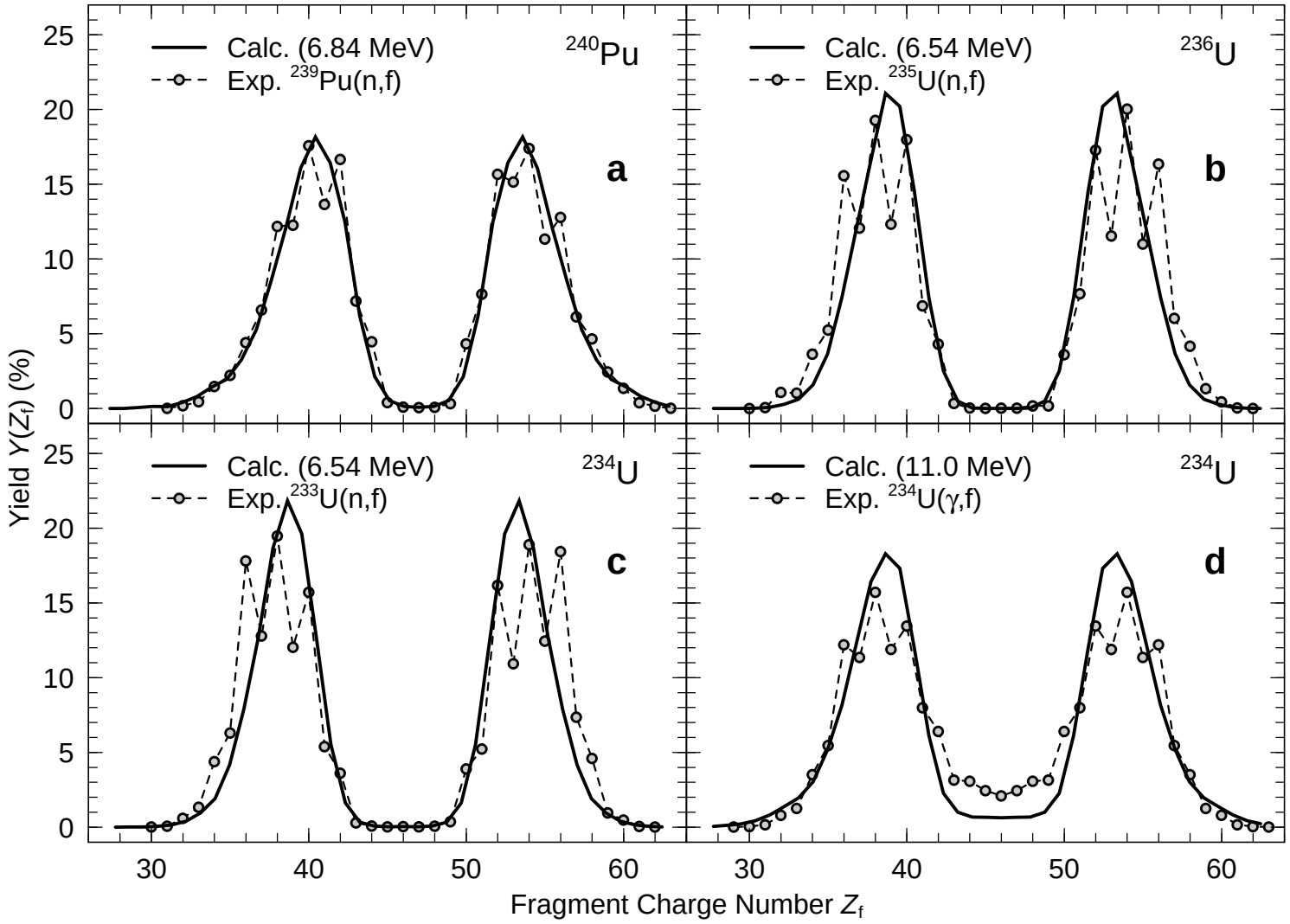
Metropolis walk:

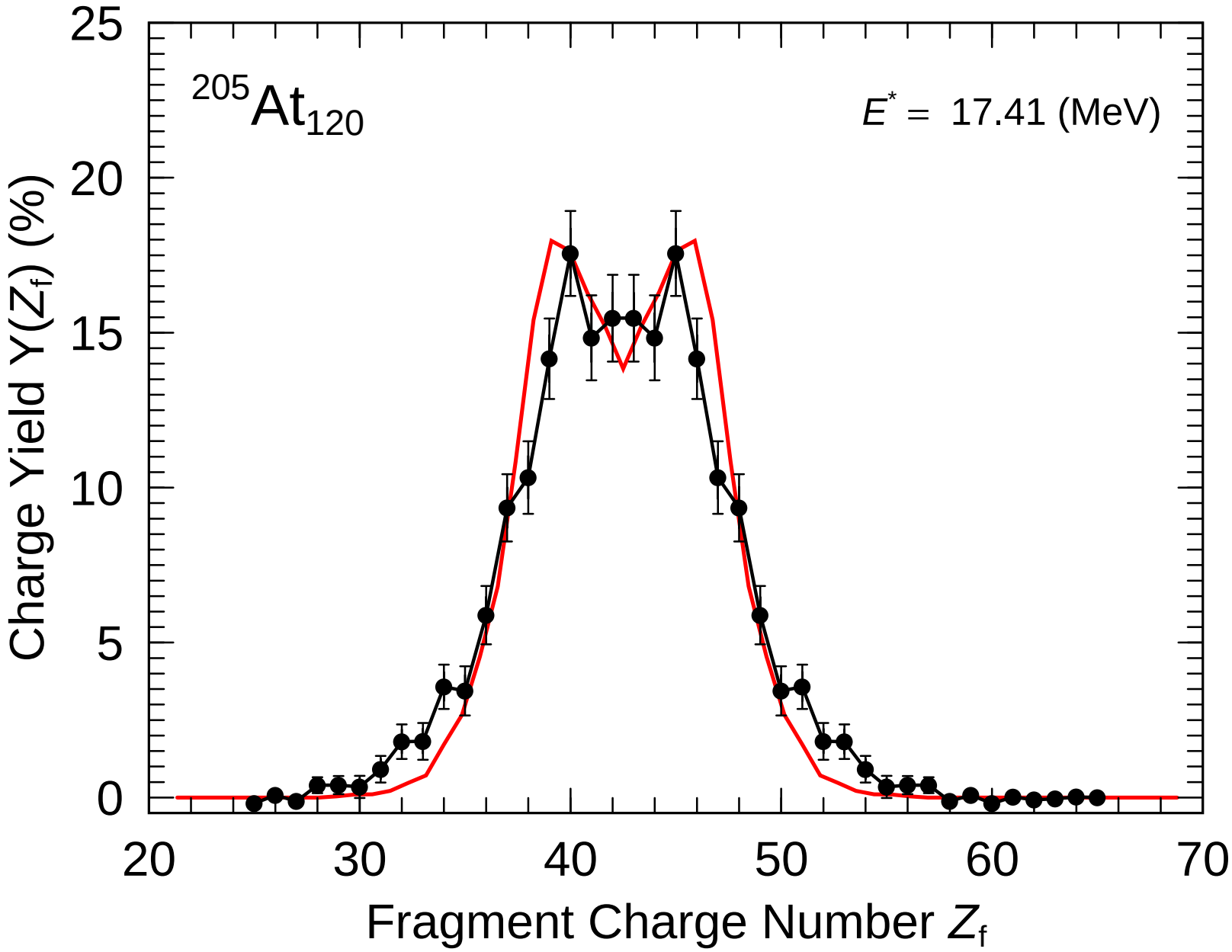
N. Metropolis *et al*, J Chem Phys 26 (1953) 1087

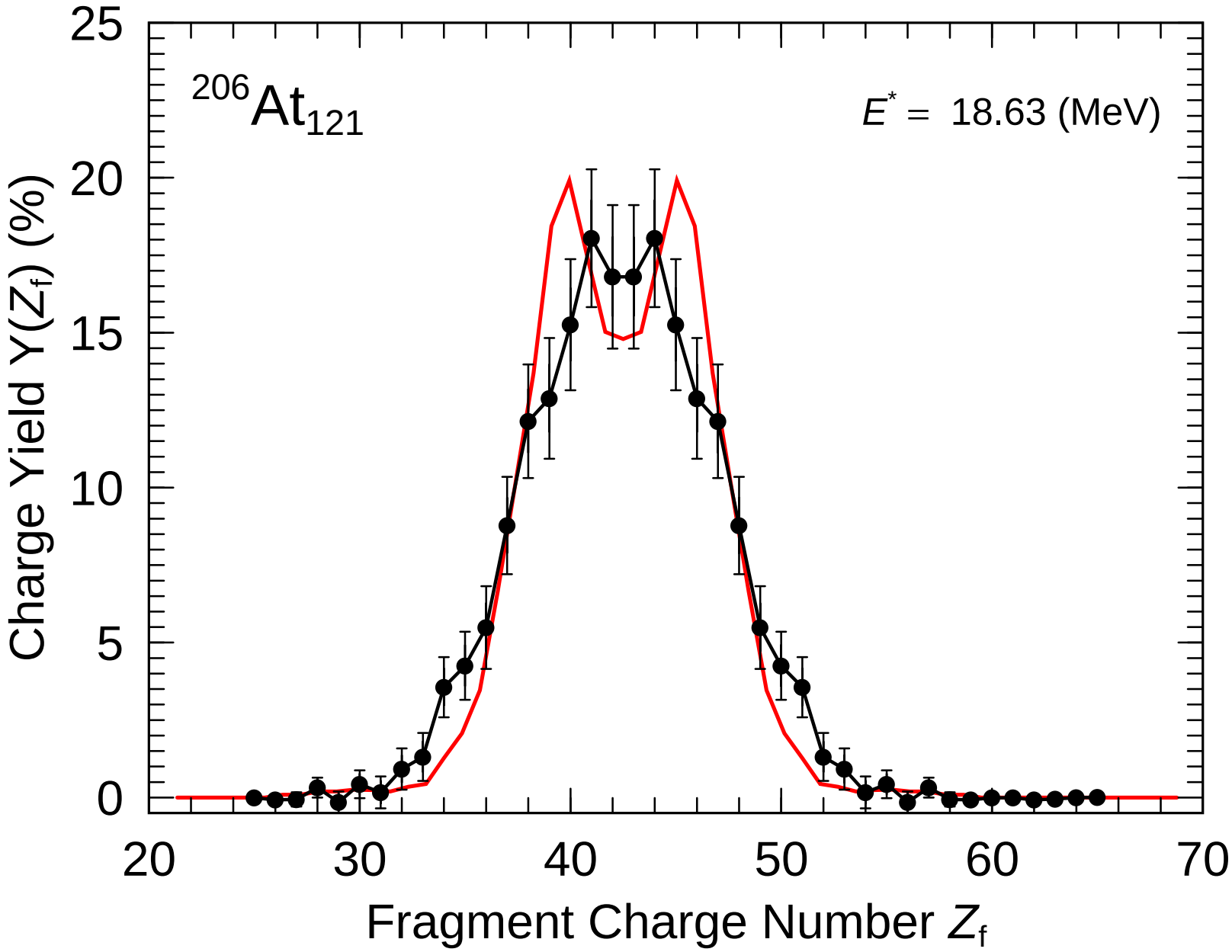
Change shape: $\chi \rightarrow \chi'$?

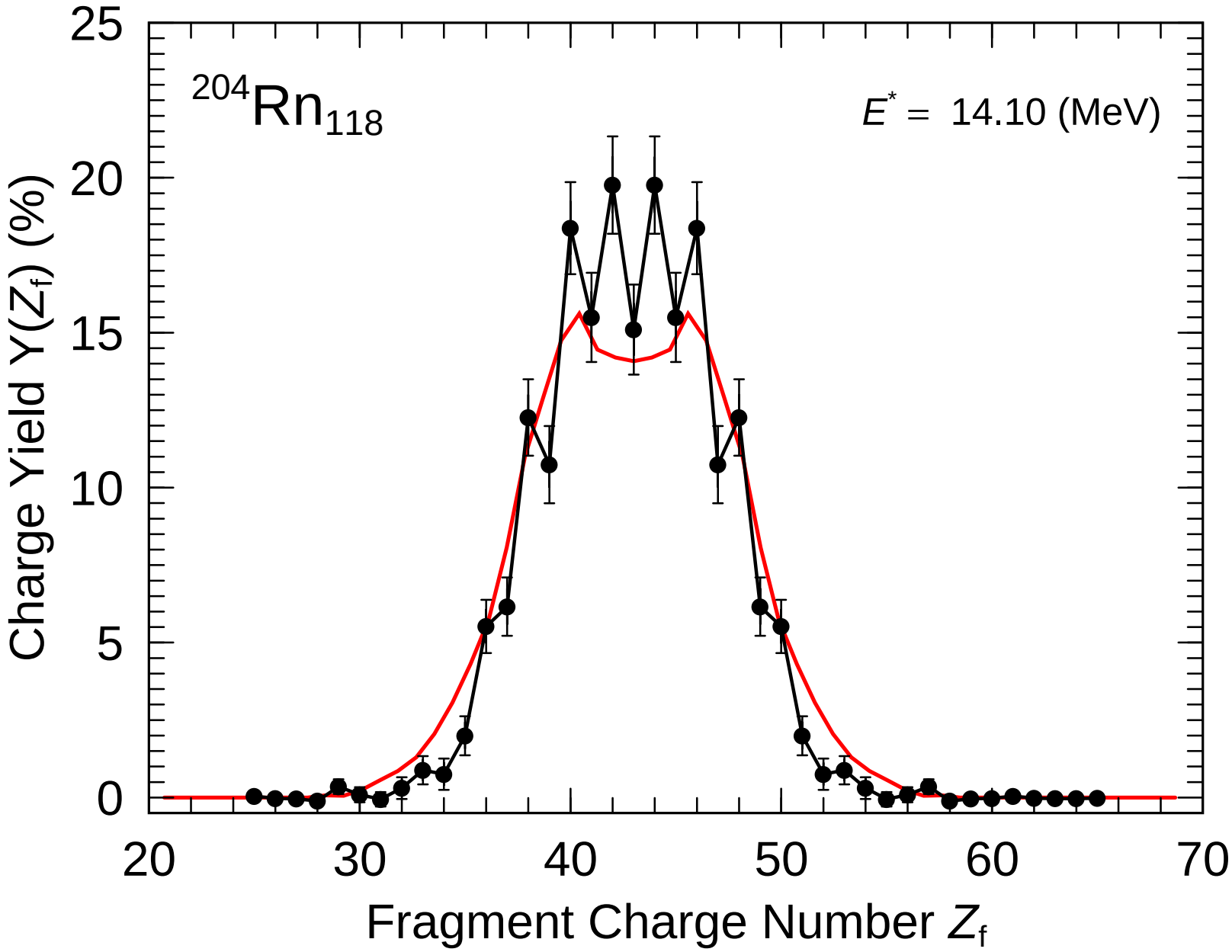
- $V(\chi') < V(\chi)$: *move with* $P = 1$
- $V(\chi') > V(\chi)$: *move with* $P = \exp(-\Delta V/T)$

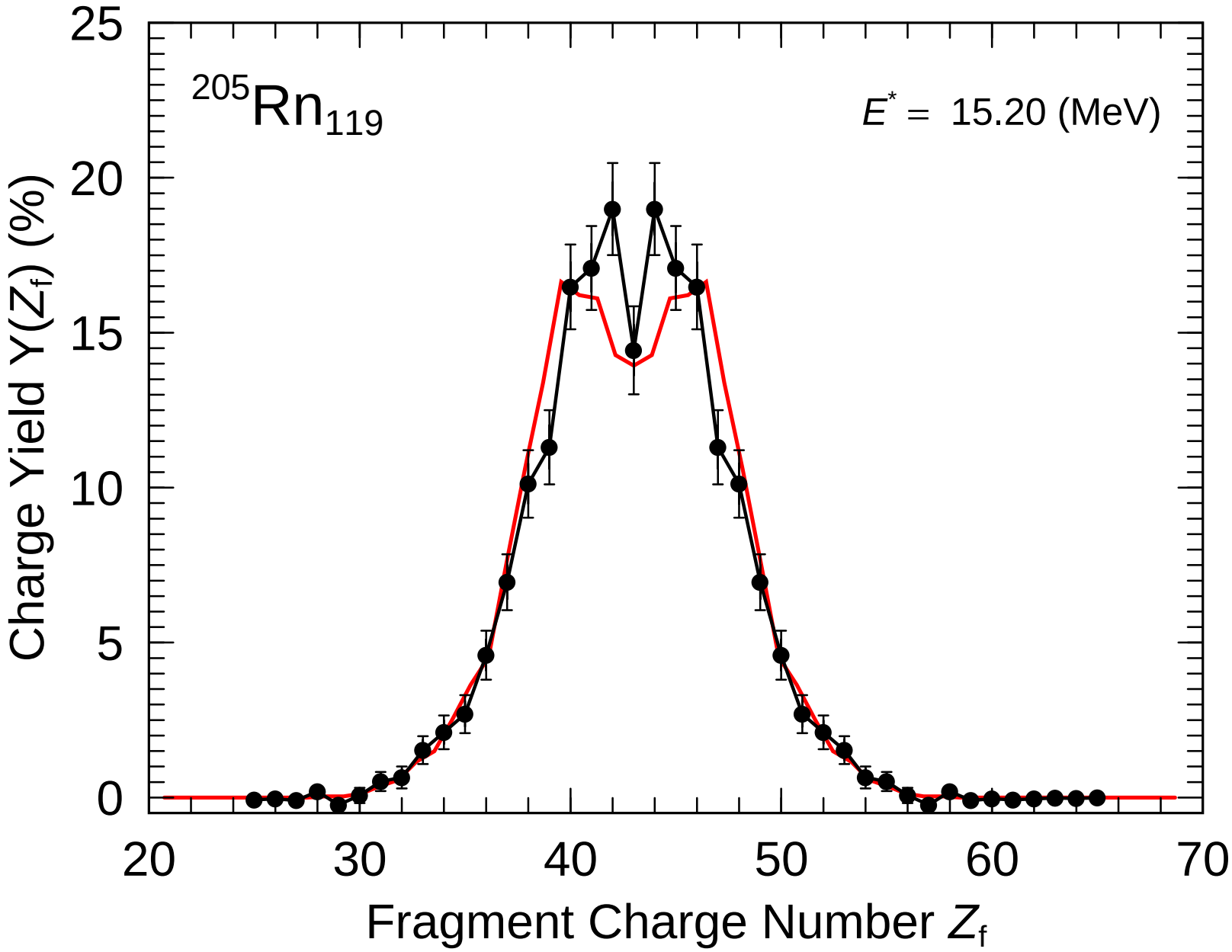
Scission: Critical neck radius $c_0 \approx 2.5$ fm

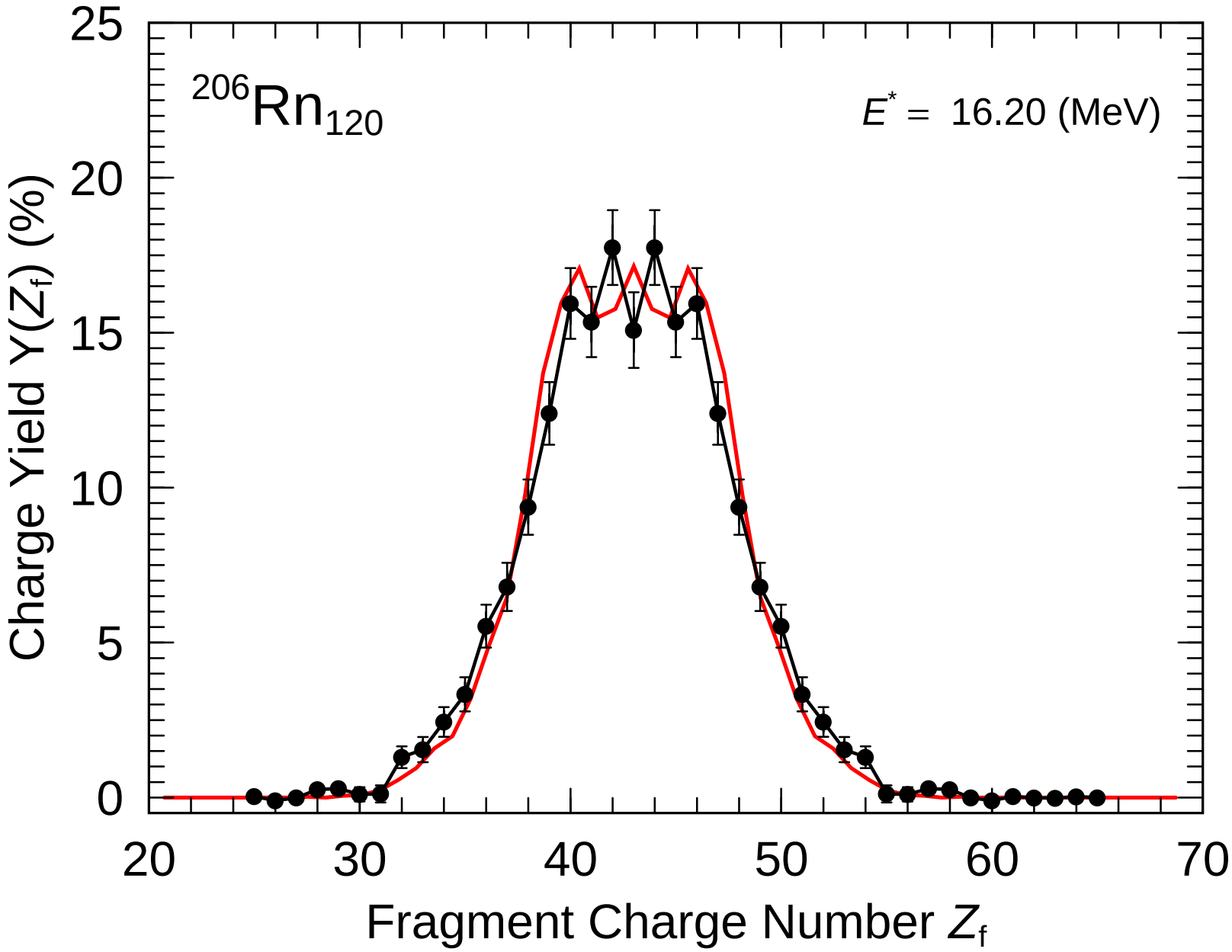

Calc. (6.84 MeV)
Exp. 239Pu(n,f)
240Pu
a
Calc. (6.54 MeV)
Exp. 235U(n,f)
236U
b
Calc. (6.54 MeV)
Exp. 233U(n,f)
234U
c
Calc. (11.0 MeV)
Exp. 234U(γ,f)
234U
d
Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

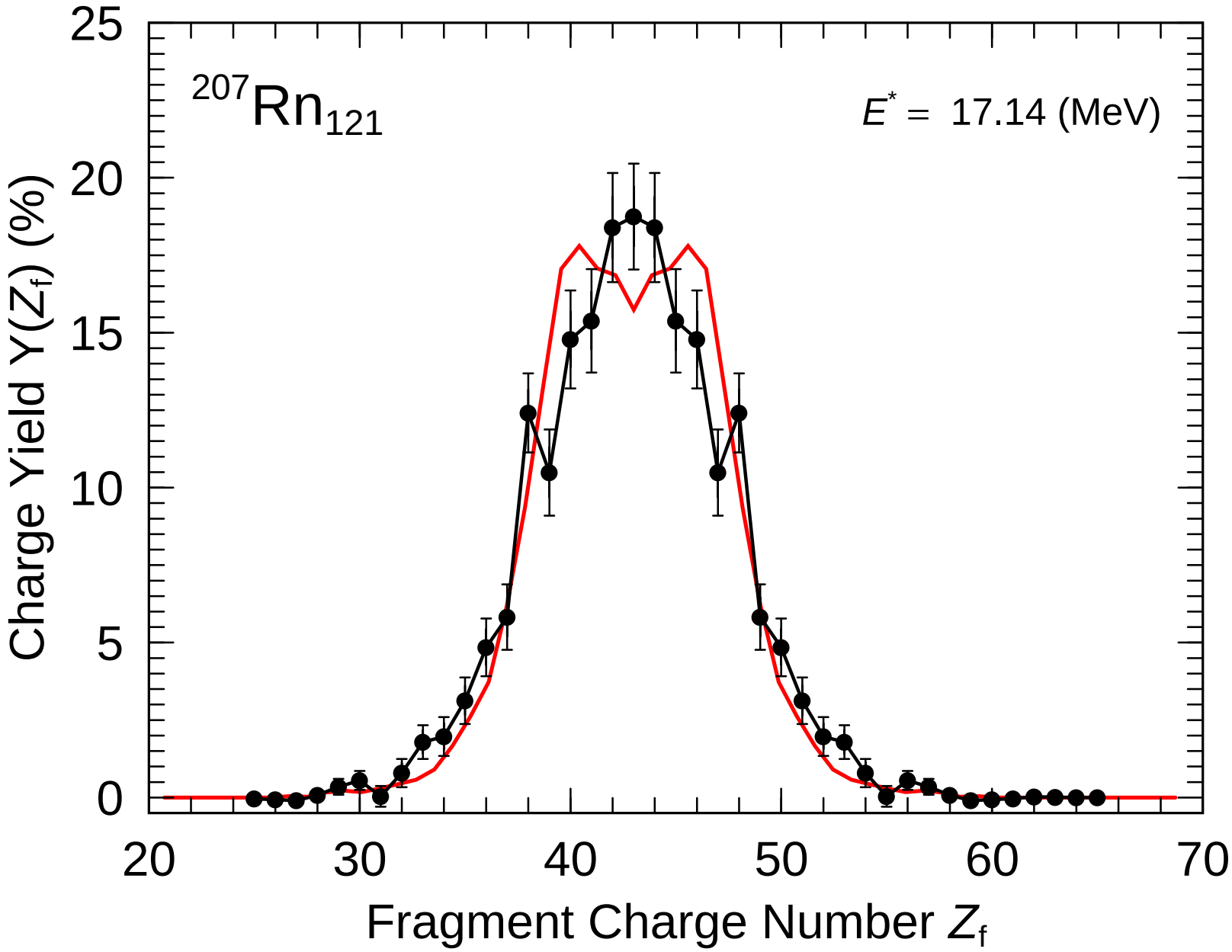

$^{205}At_{120}$
E^* = 17.41 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

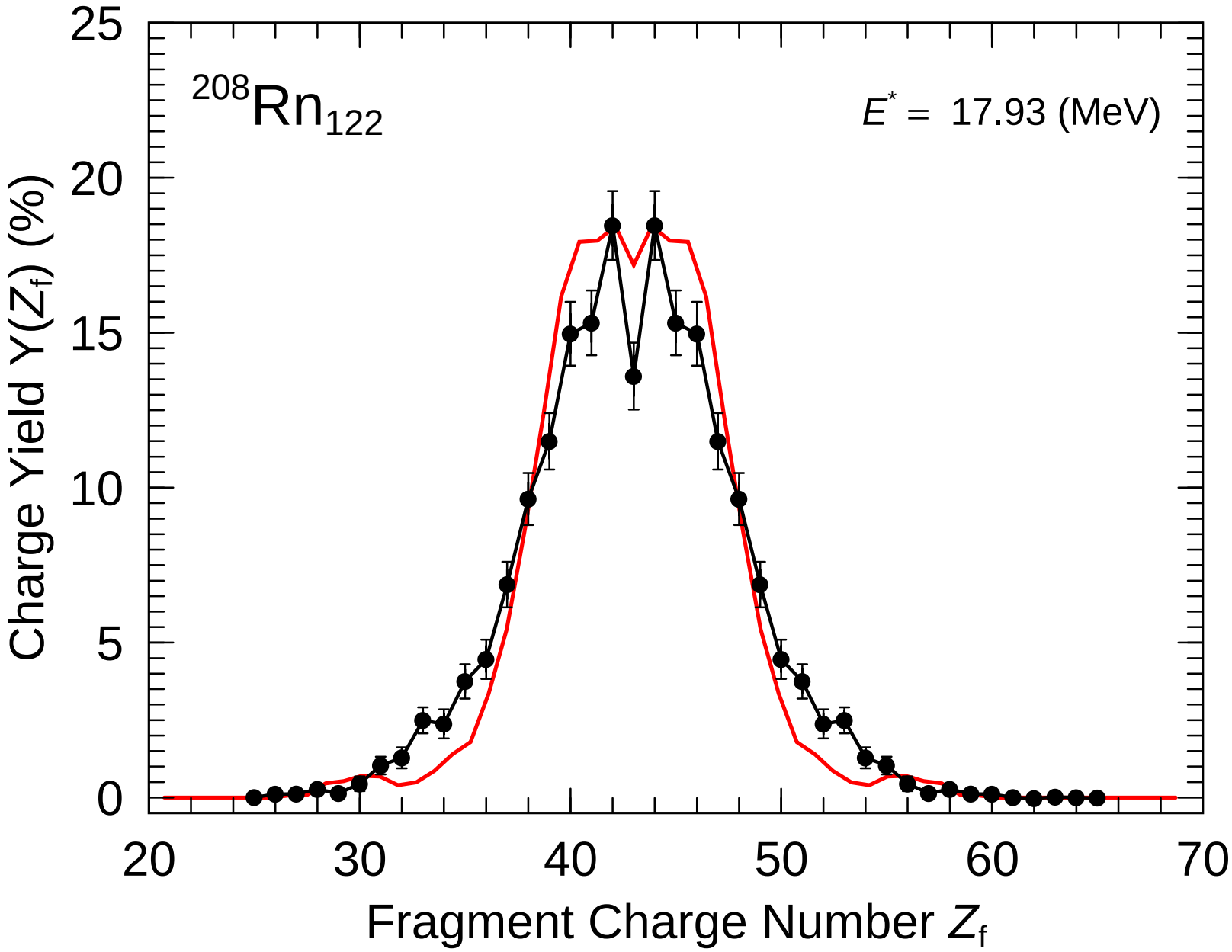

$^{206}At_{121}$
E^* = 18.63 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

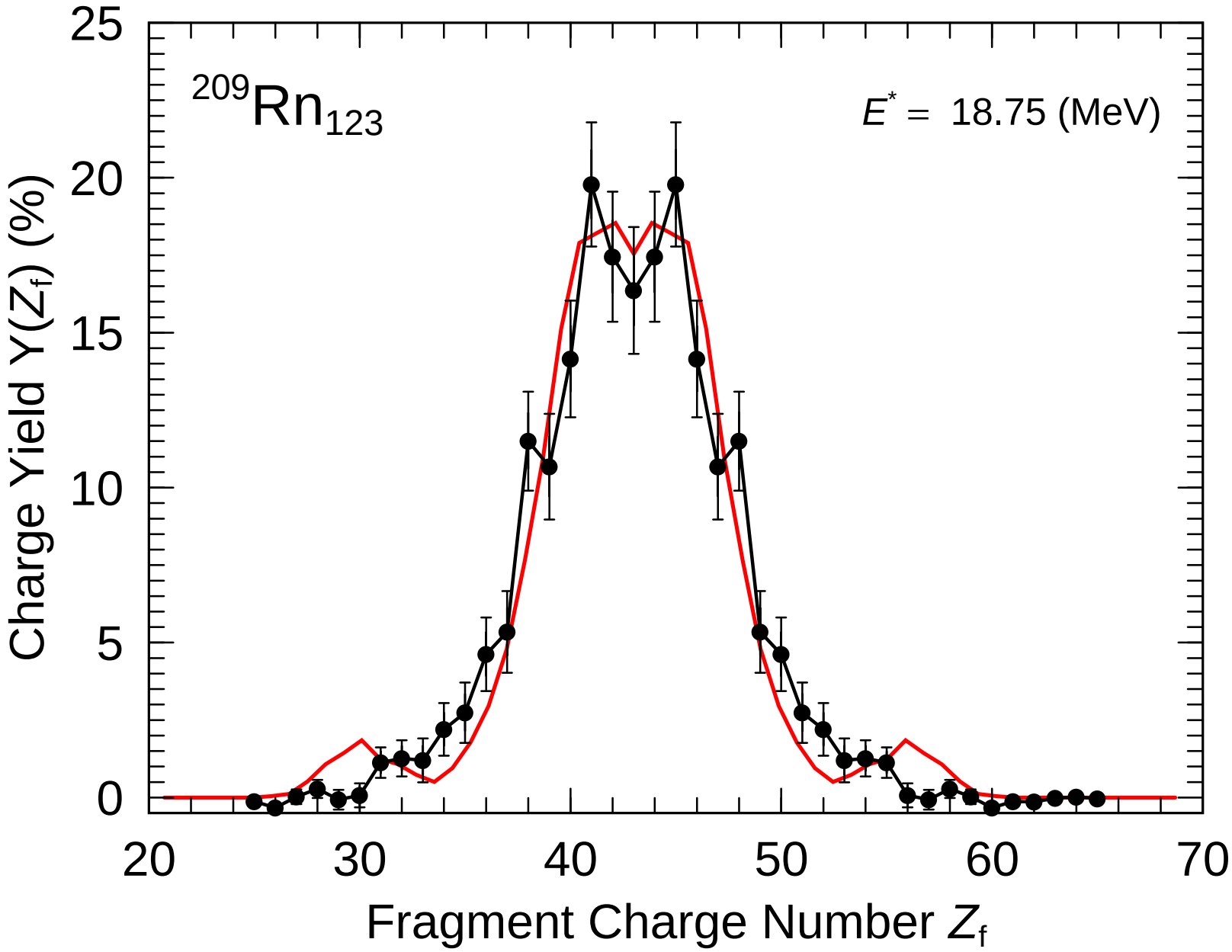

$^{204}Rn_{118}$
E^* = 14.10 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

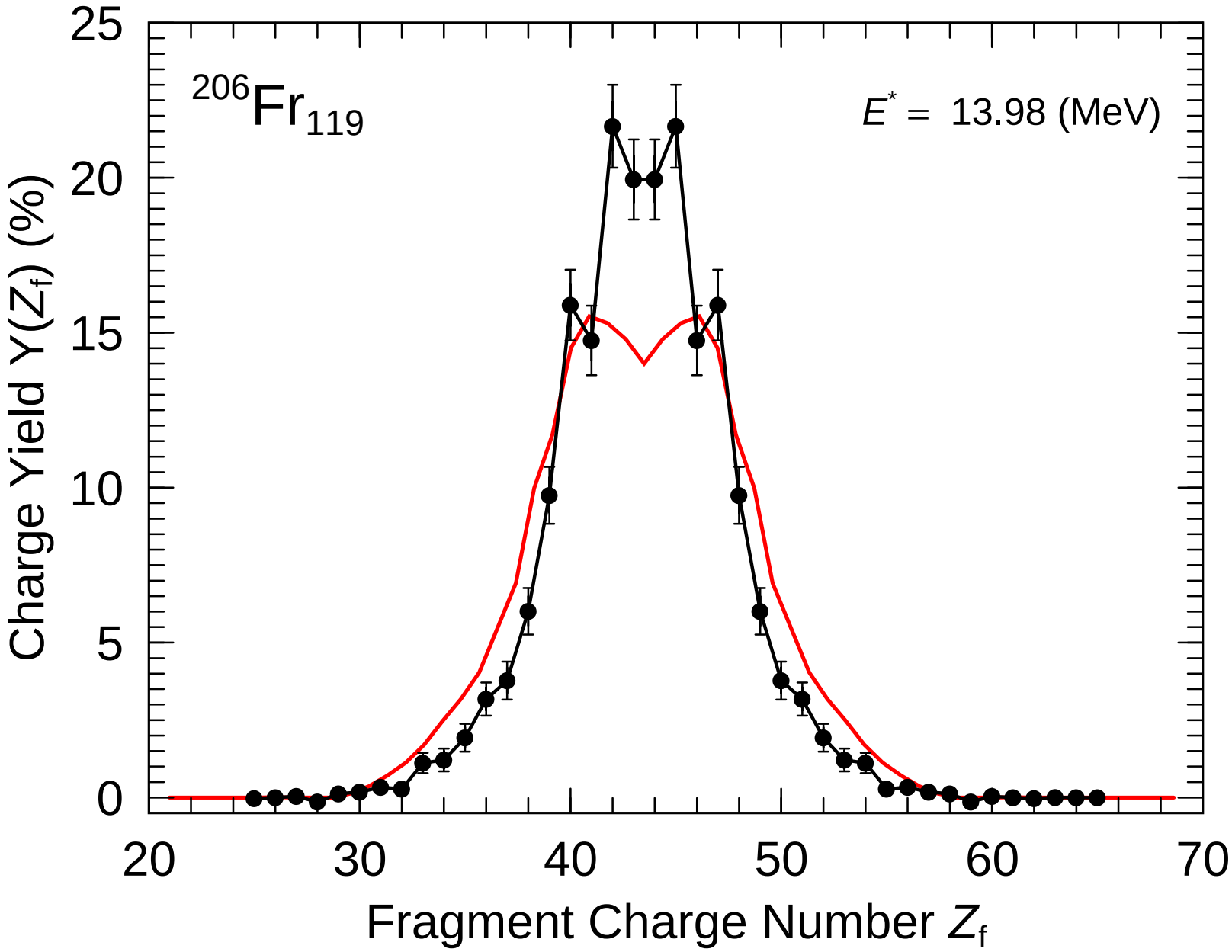

$^{205}Rn_{119}$
E^* = 15.20 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

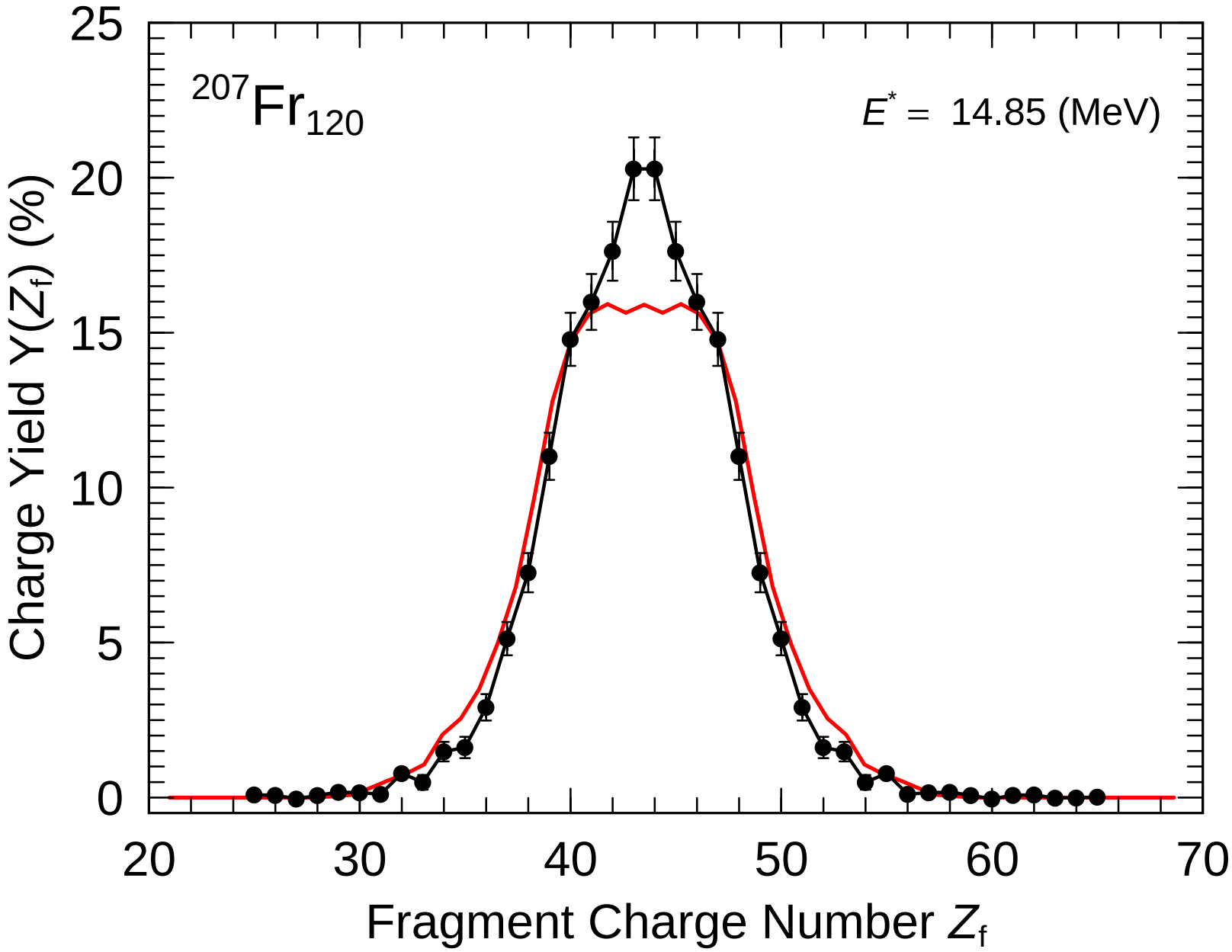

$^{206}Rn_{120}$
E^* = 16.20 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

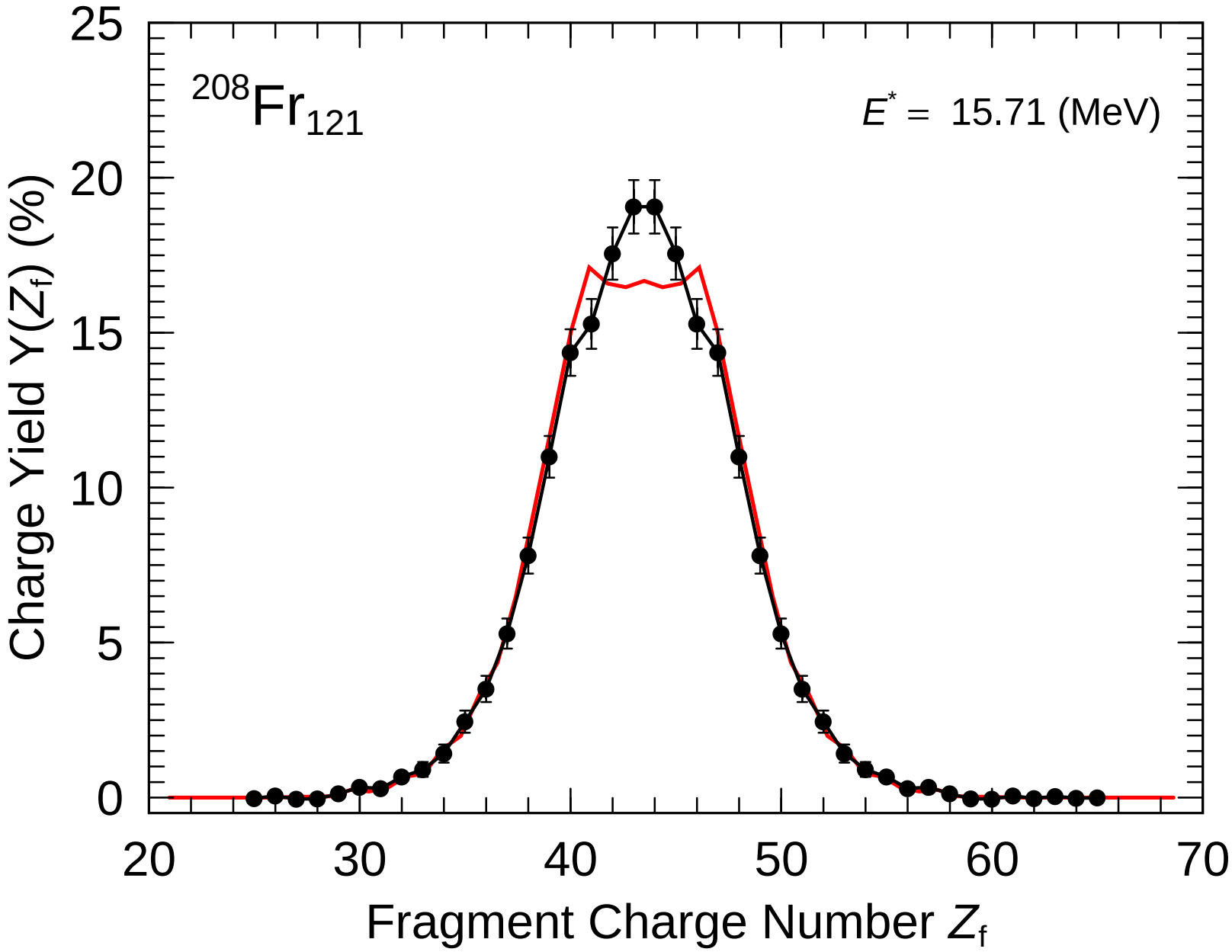

$^{207}Rn_{121}$
E^* = 17.14 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

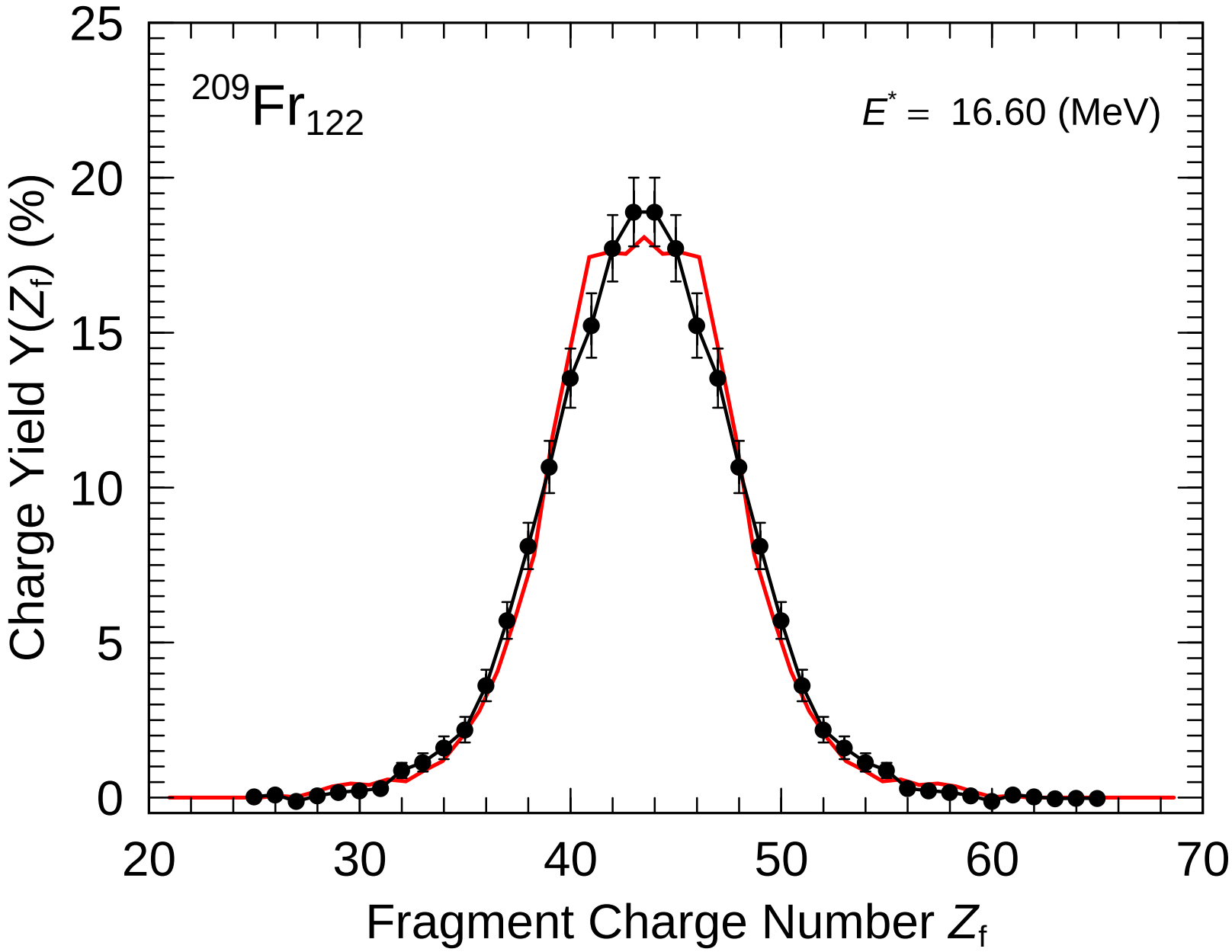

$^{208}Rn_{122}$
E^* = 17.93 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

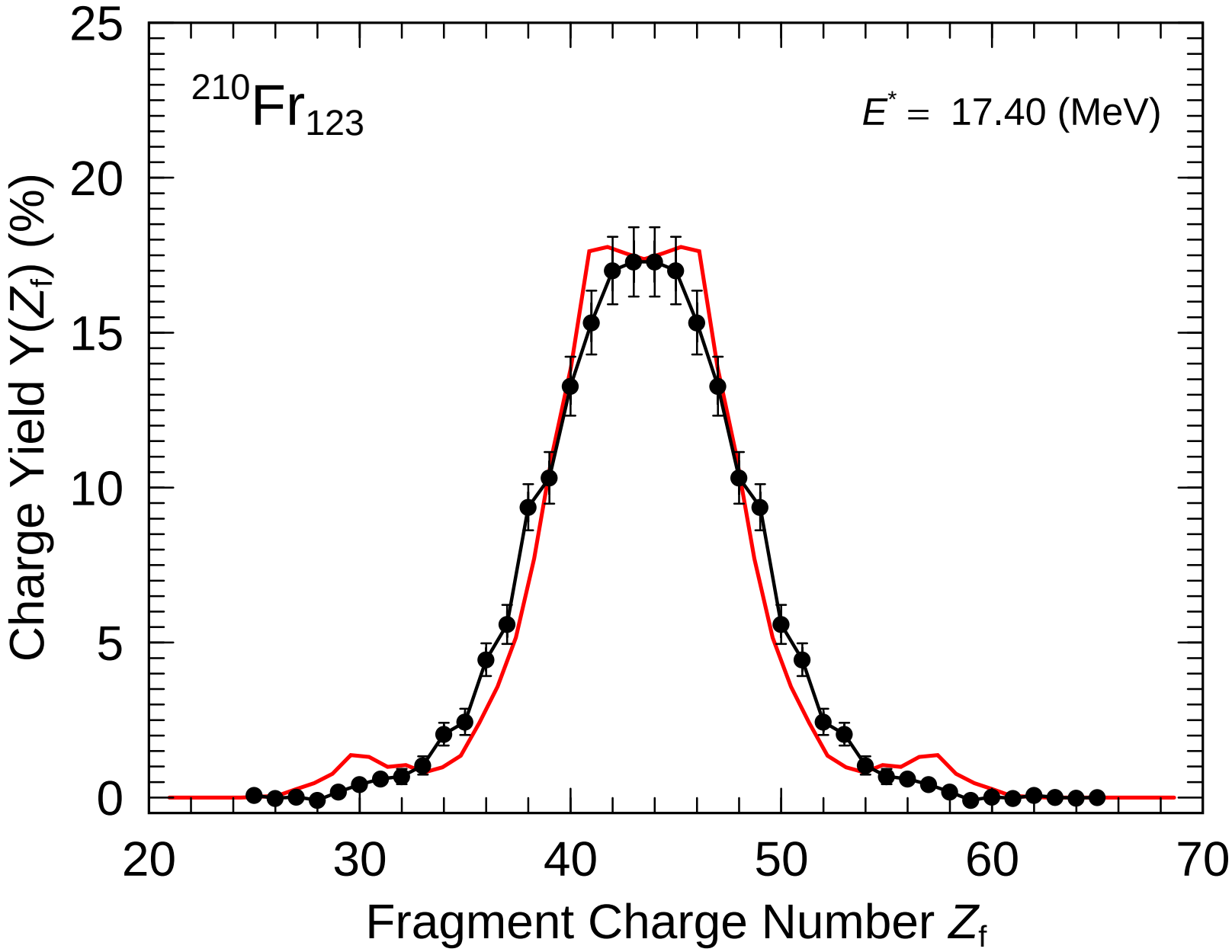

$^{209}Rn_{123}$
E^* = 18.75 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

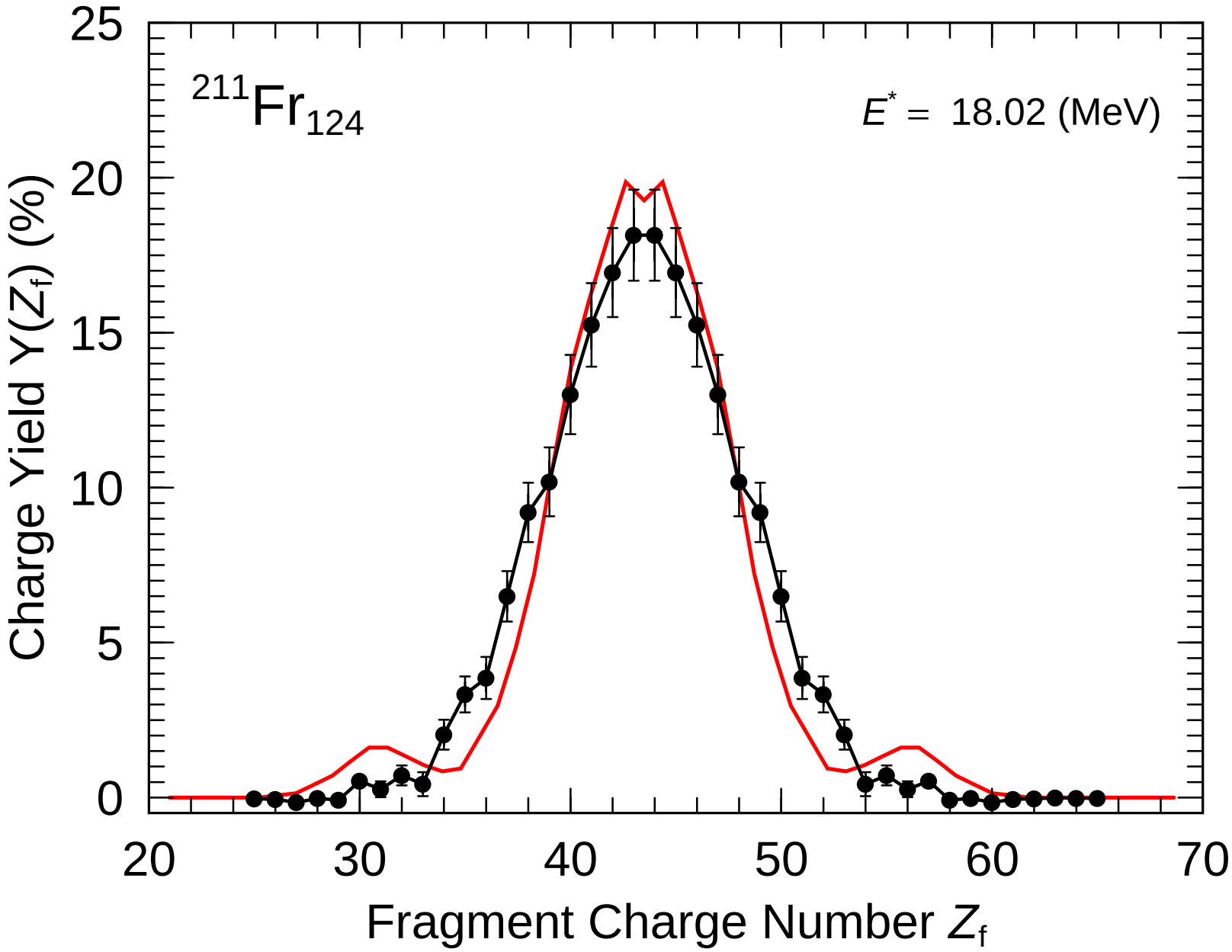

$^{206}Fr_{119}$
E^* = 13.98 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

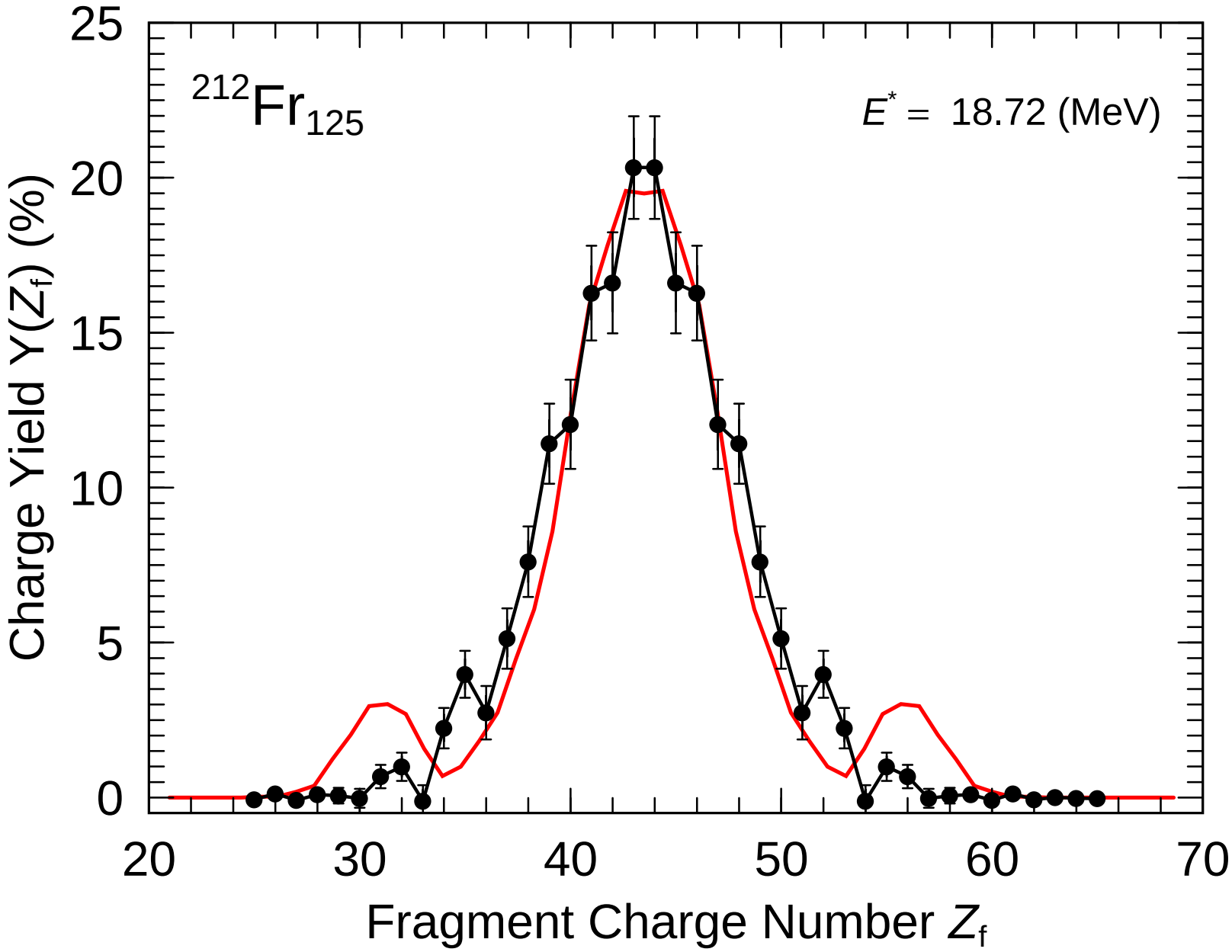

$^{207}Fr_{120}$
E^* = 14.85 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

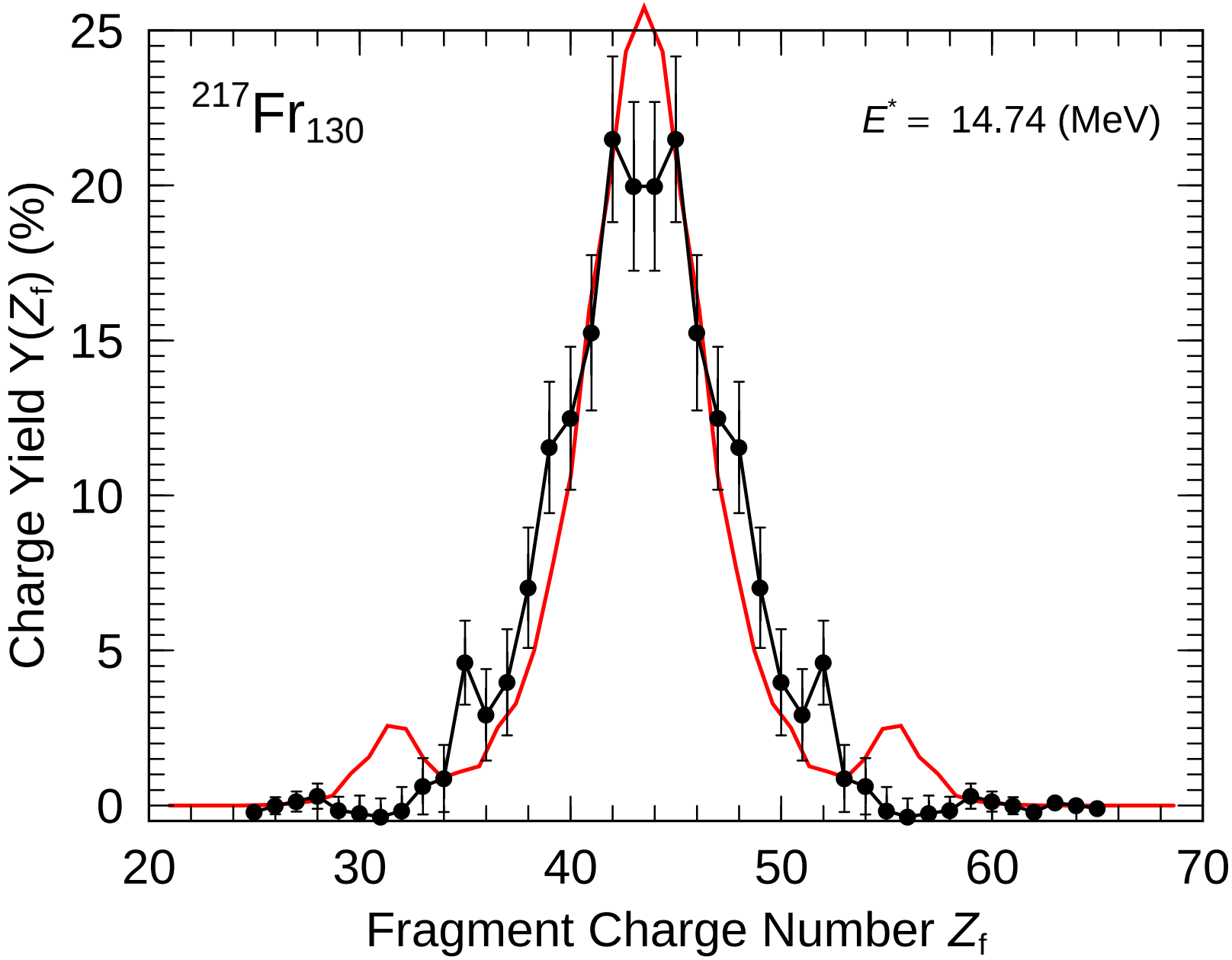

$^{208}Fr_{121}$
E^* = 15.71 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

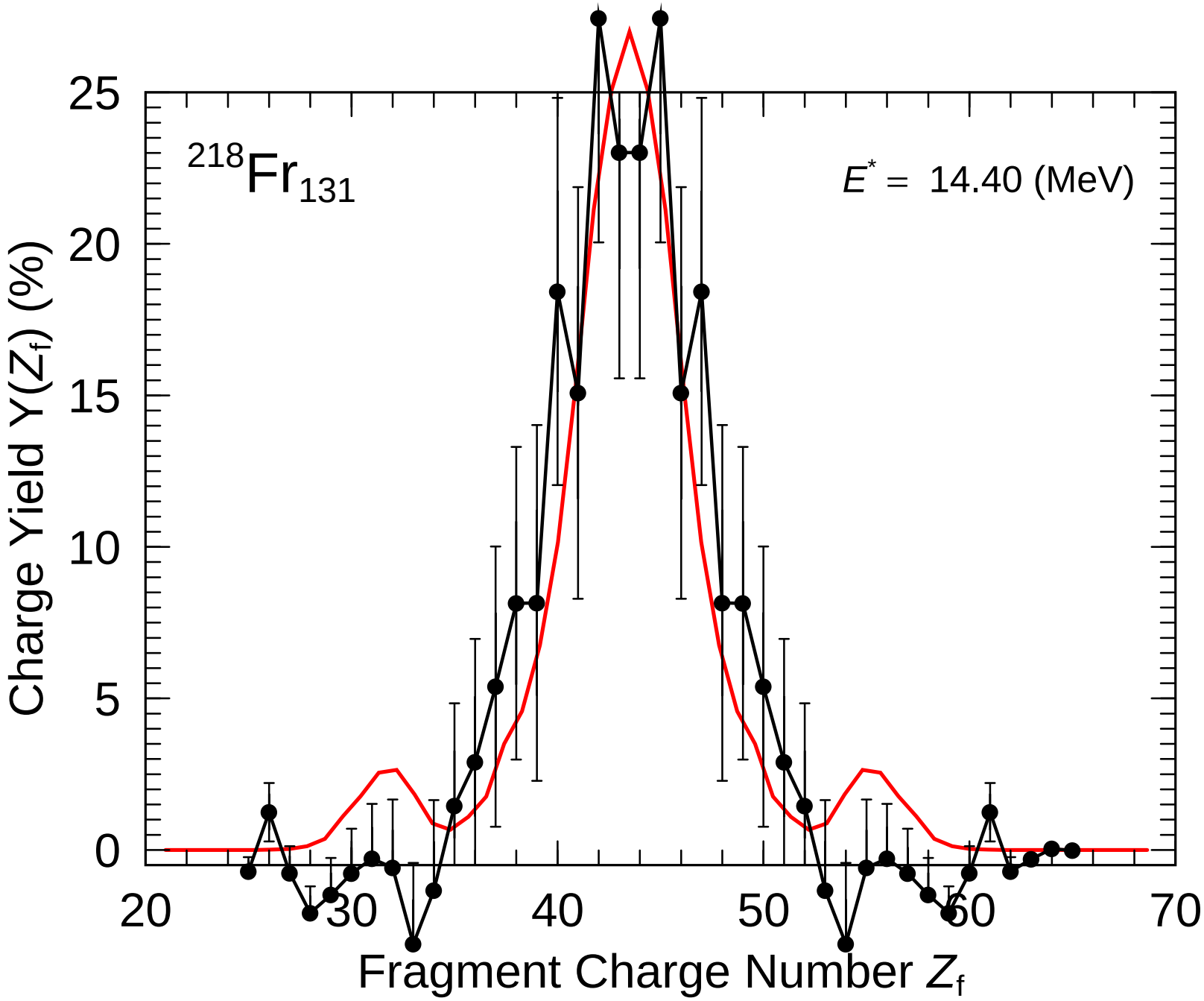

$^{209}Fr_{122}$
E^* = 16.60 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

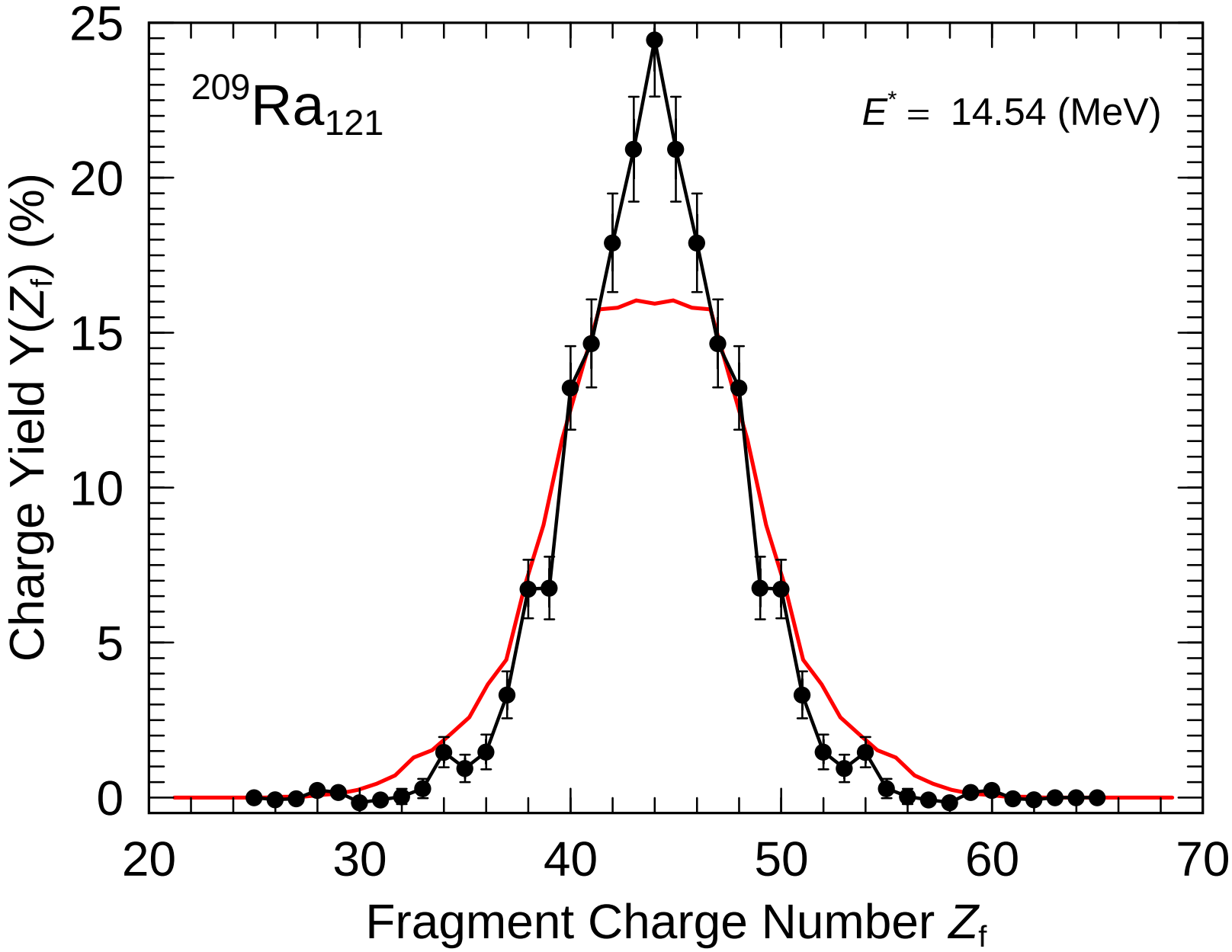

$^{210}Fr_{123}$
E^* = 17.40 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

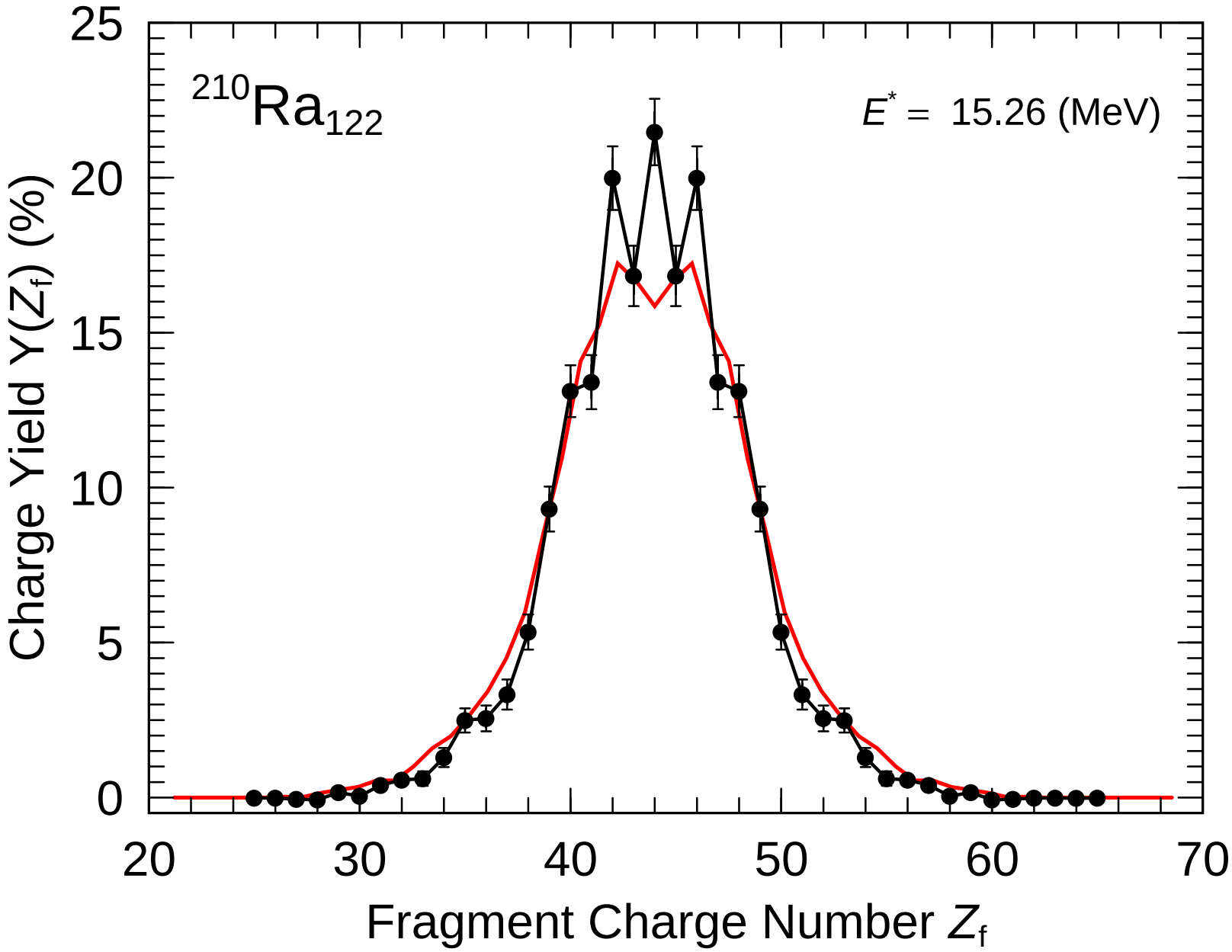

$^{211}Fr_{124}$
E^* = 18.02 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

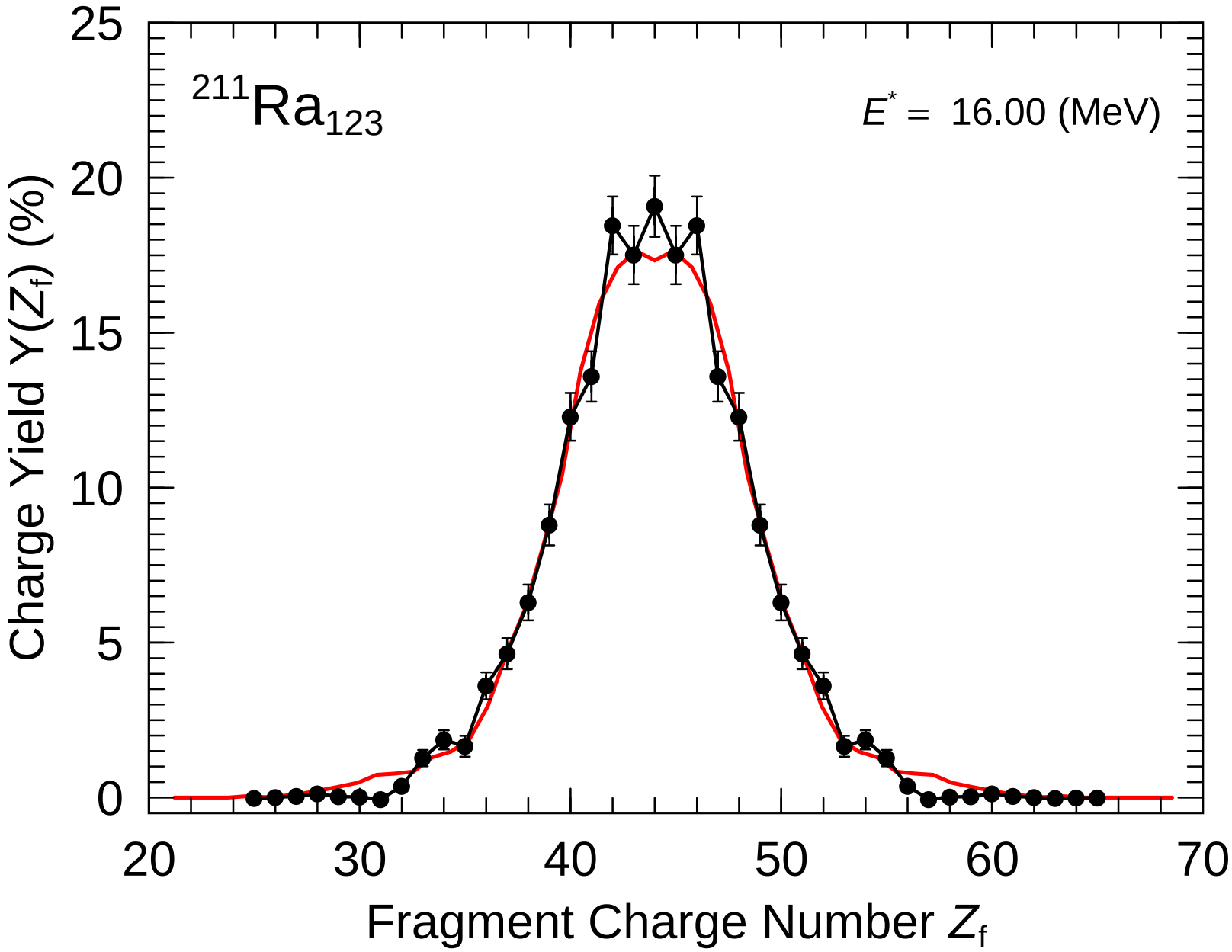

$^{212}Fr_{125}$
E^* = 18.72 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

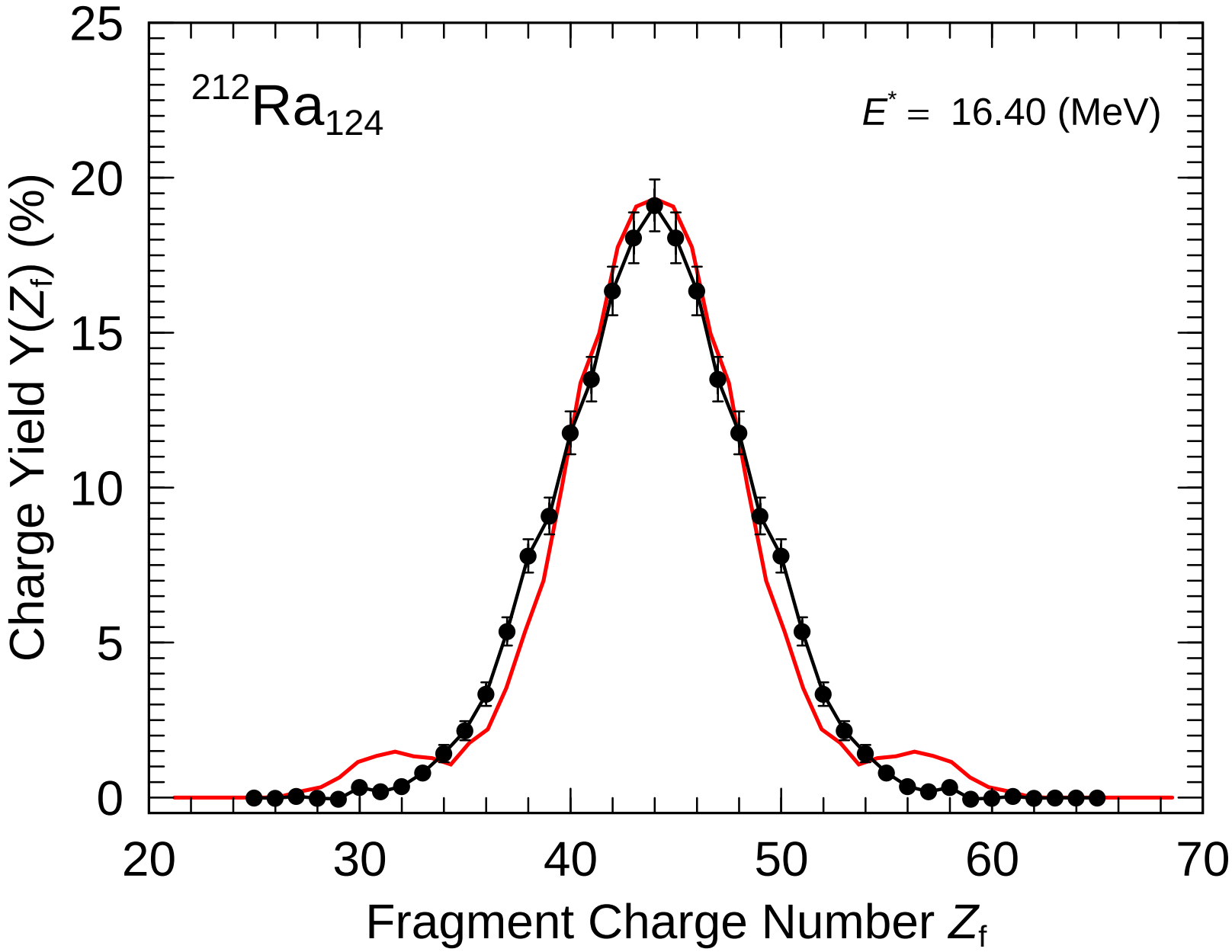

$^{217}Fr_{130}$
E^* = 14.74 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70


$^{218}Fr_{131}$
E^* = 14.40 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70


$^{209}Ra_{121}$
E^* = 14.54 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70


$^{210}Ra_{122}$
E^* = 15.26 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70


$^{211}Ra_{123}$
E^* = 16.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70


$^{212}Ra_{124}$
E^* = 16.40 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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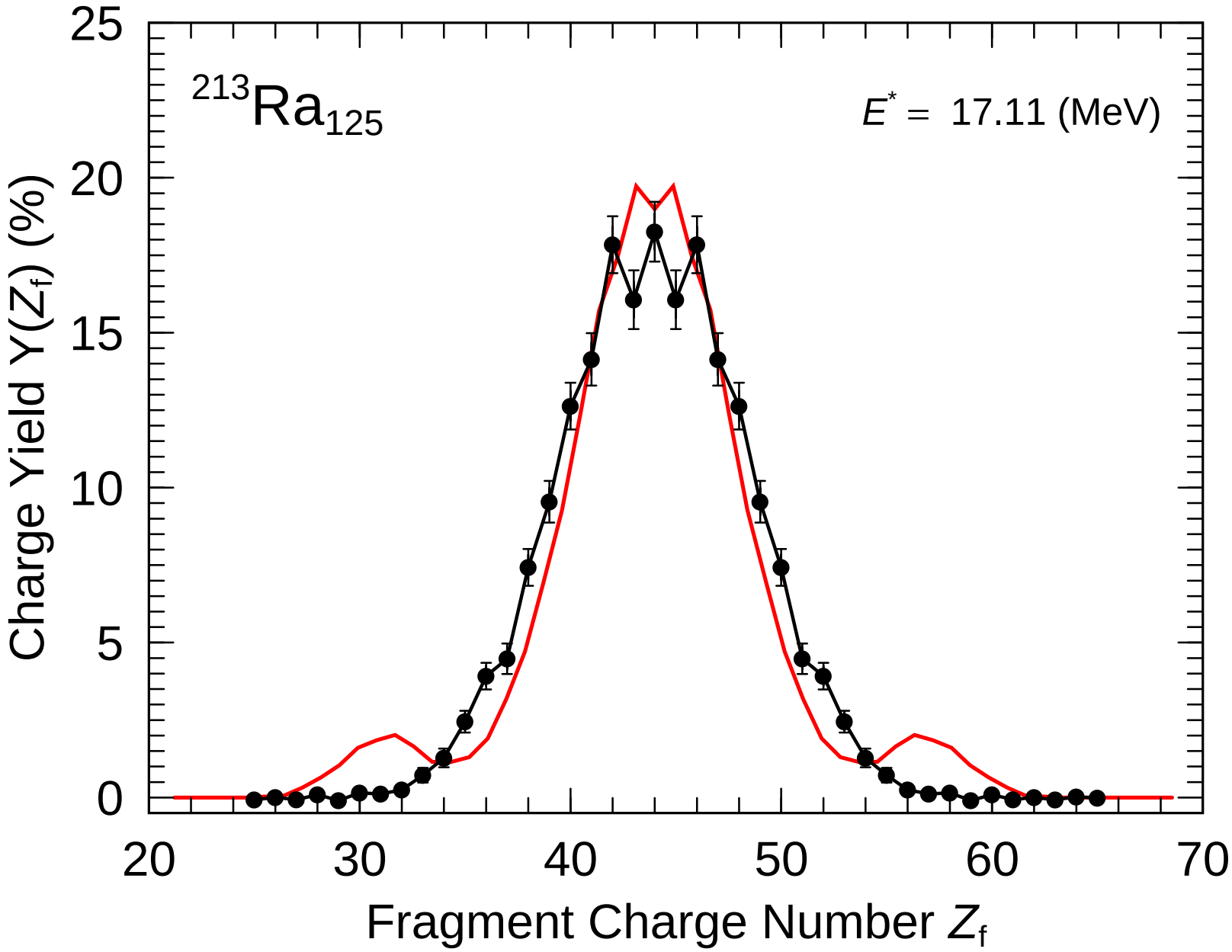
$^{213}Ra_{125}$
E^* = 17.11 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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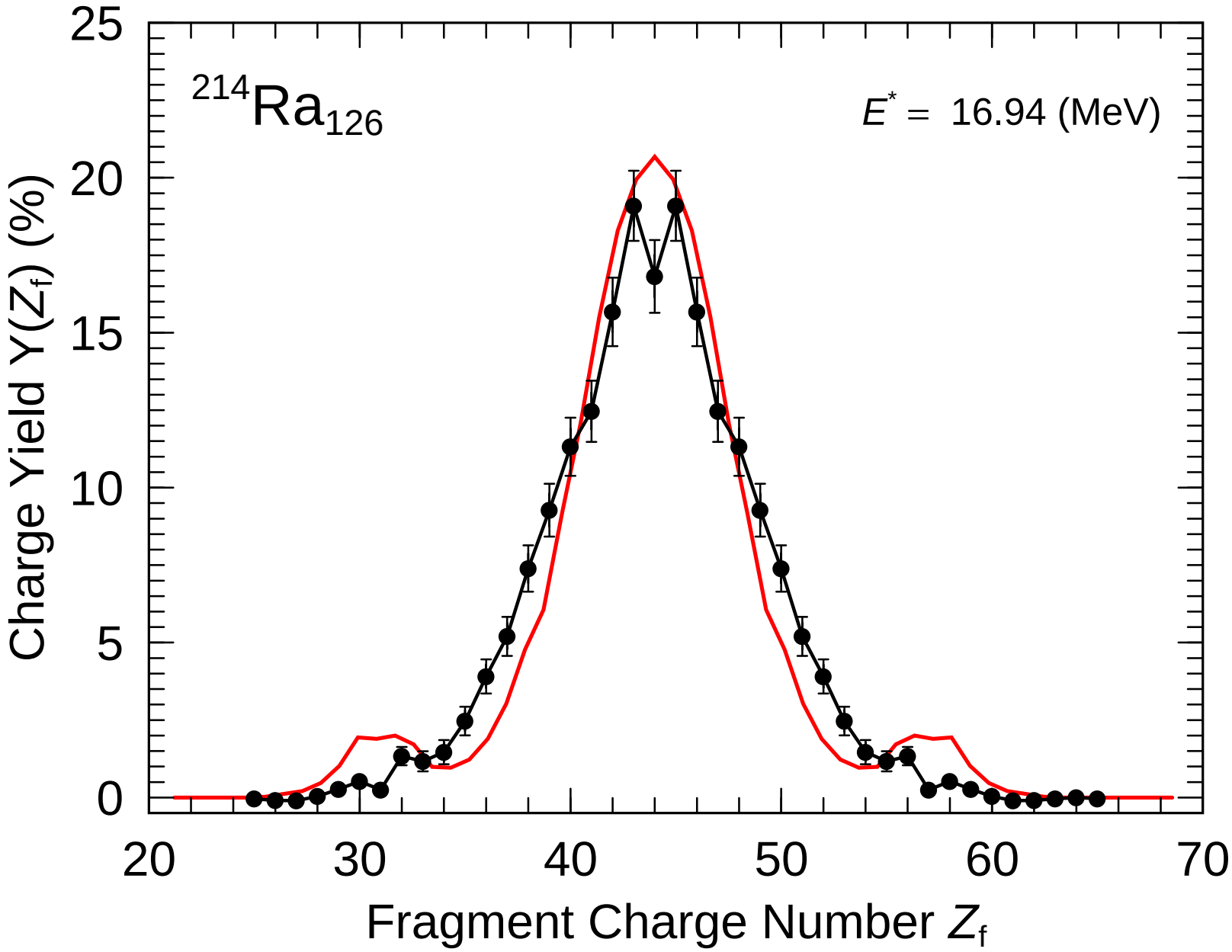
$^{214}Ra_{126}$
E^* = 16.94 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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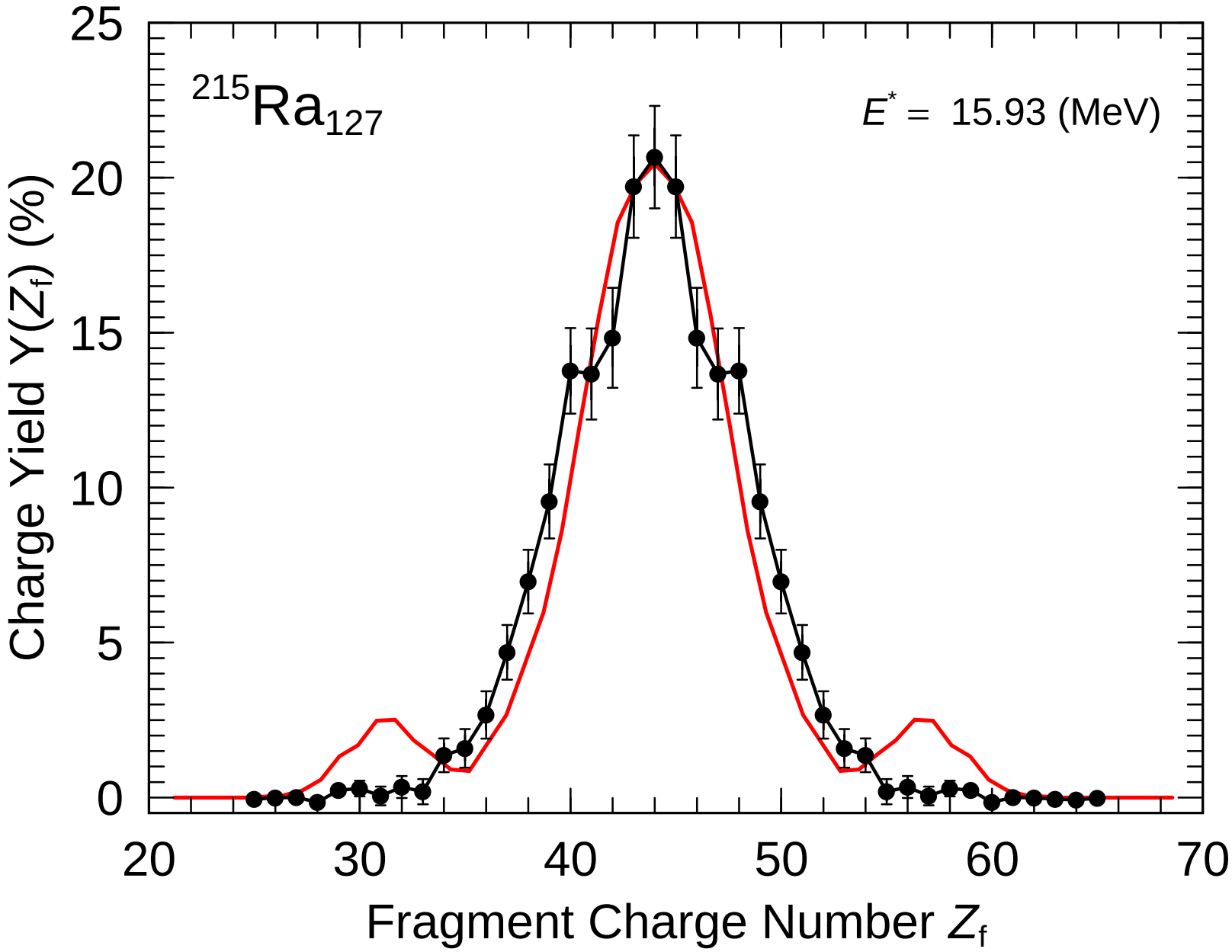
$^{215}Ra_{127}$
E^* = 15.93 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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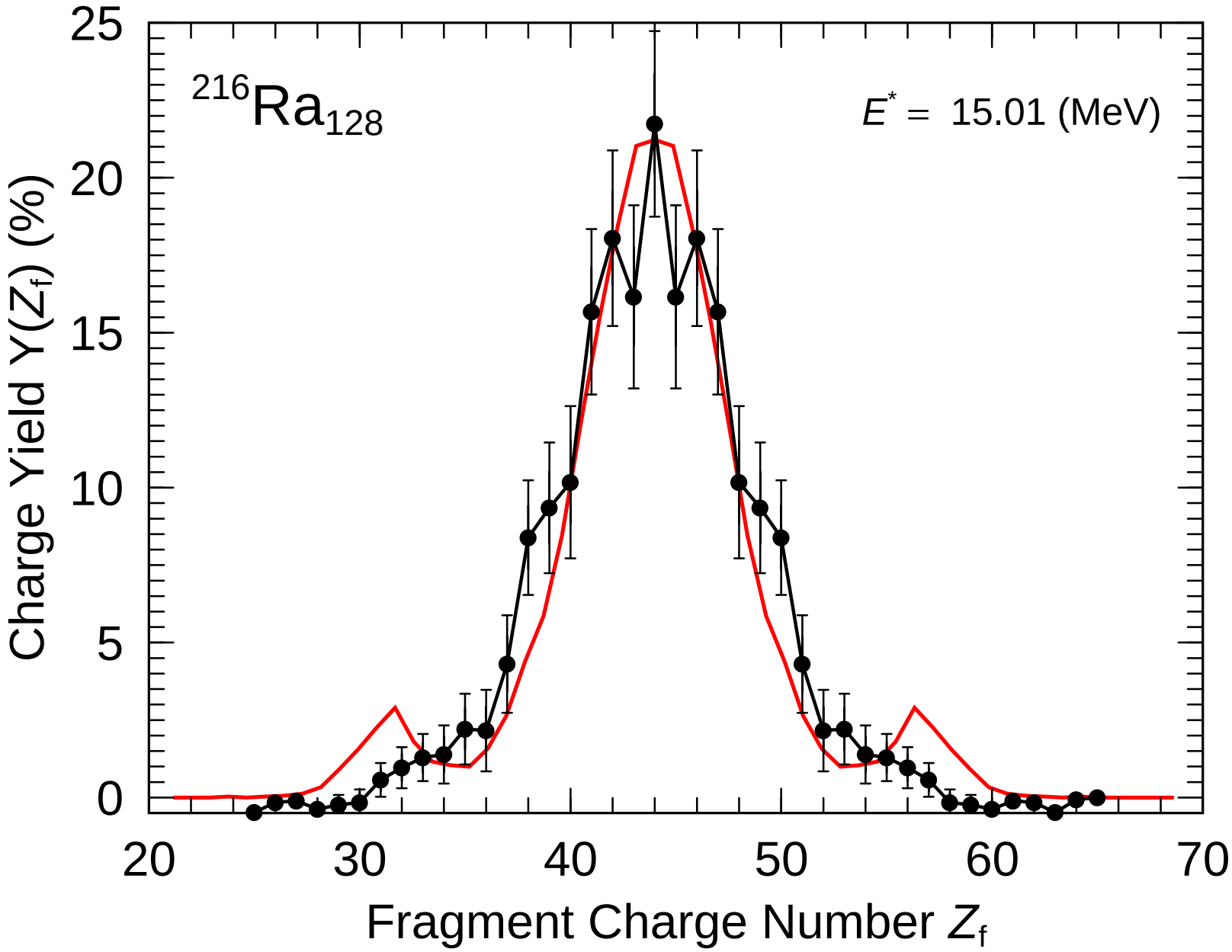
$^{216}Ra_{128}$
E^* = 15.01 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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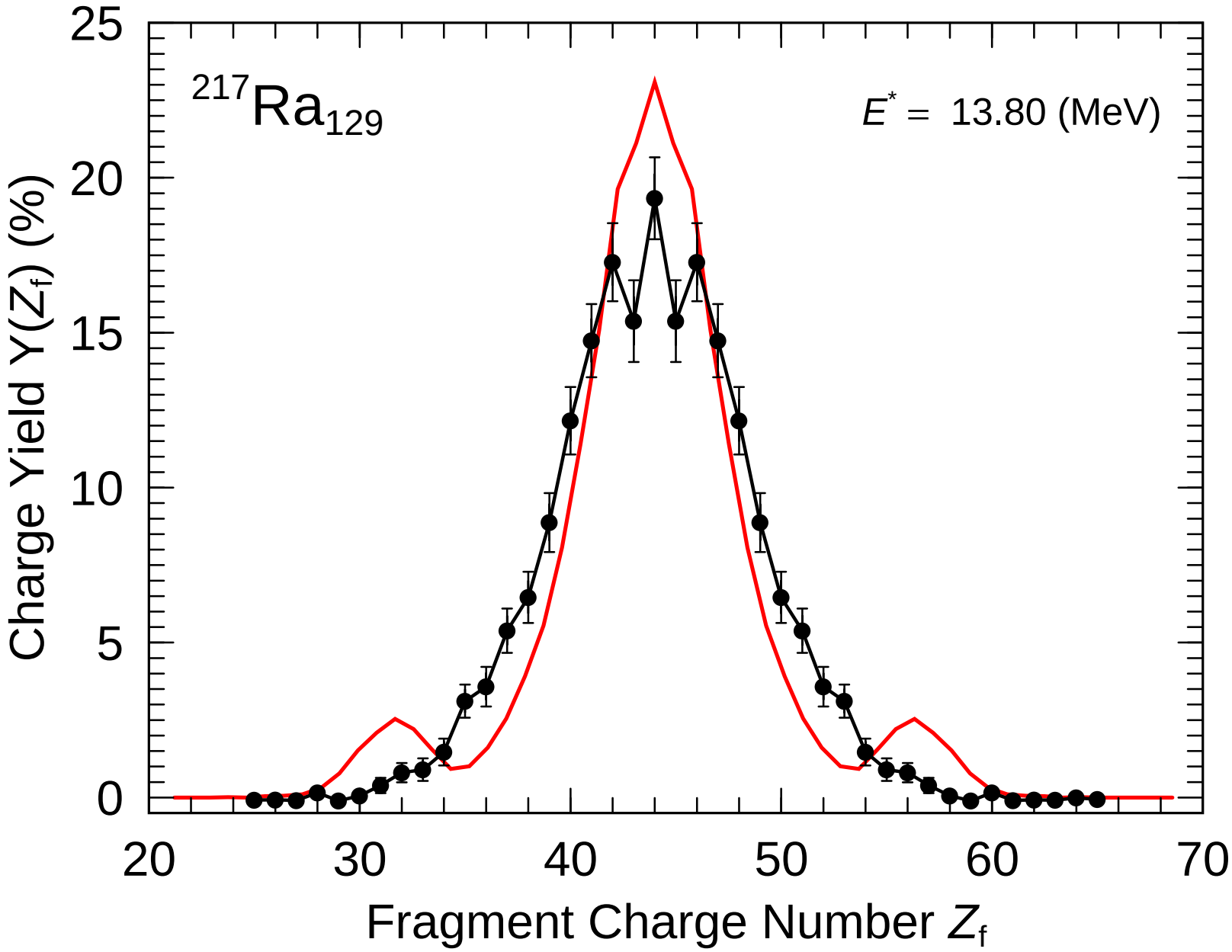
$^{217}Ra_{129}$
E^* = 13.80 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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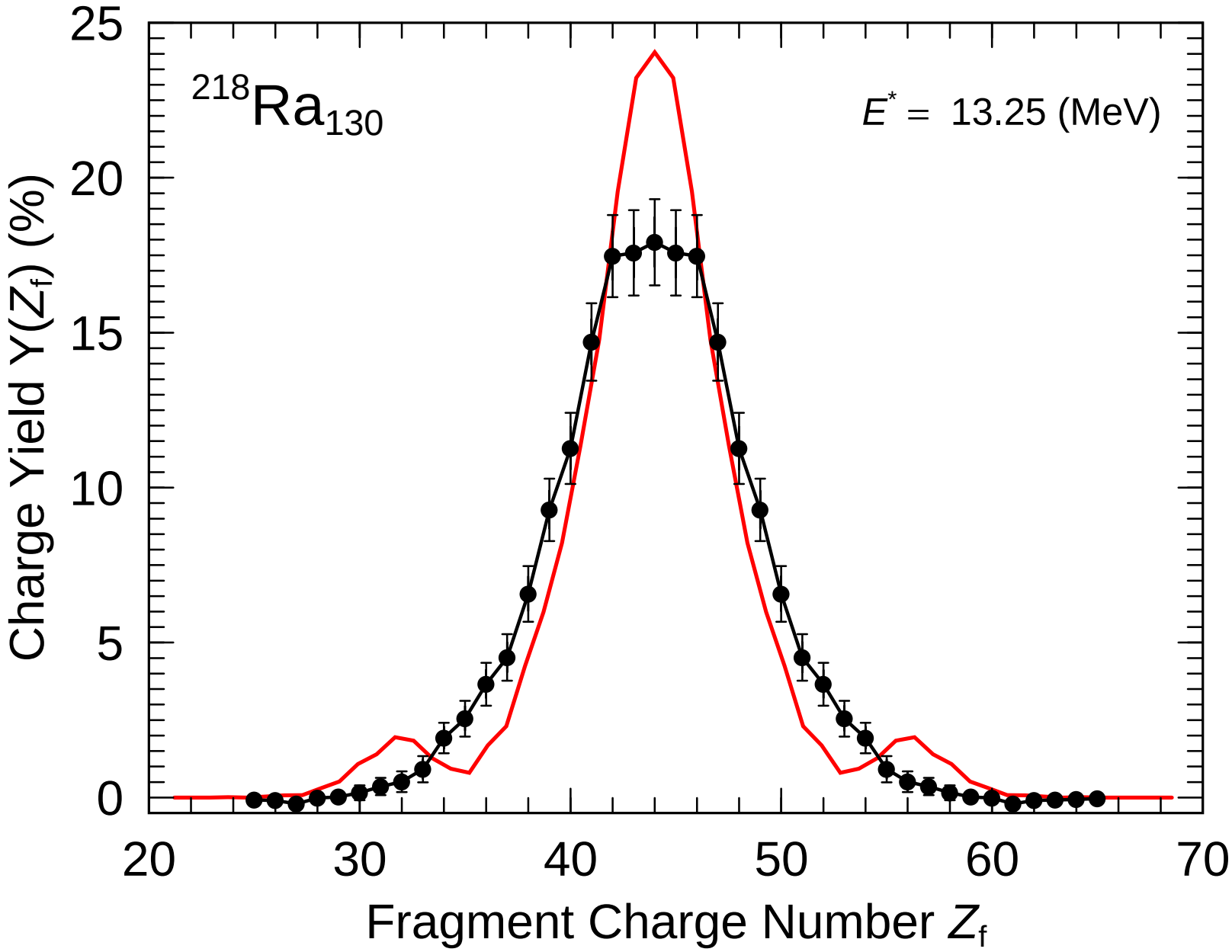
$^{218}Ra_{130}$
E^* = 13.25 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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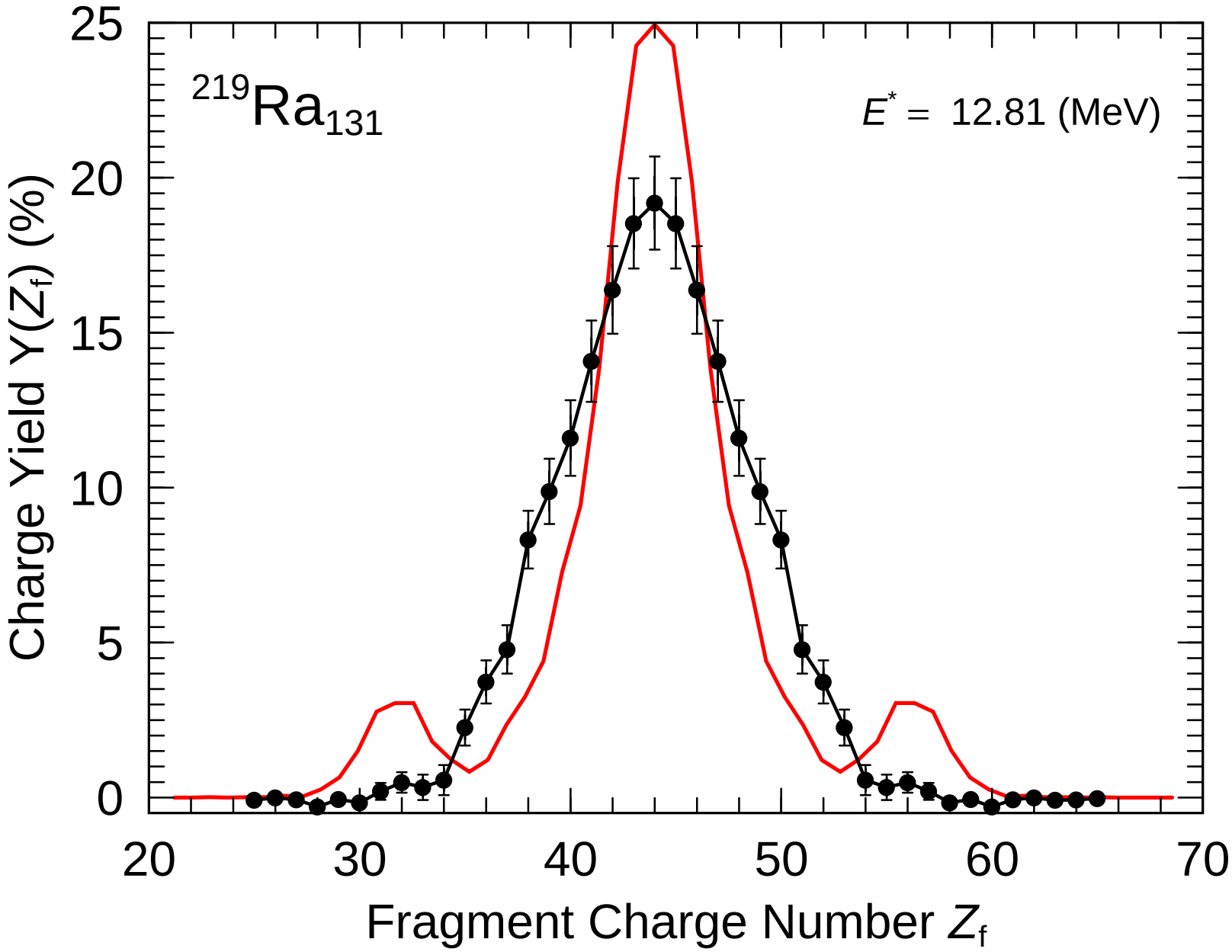
$^{219}Ra_{131}$
E^* = 12.81 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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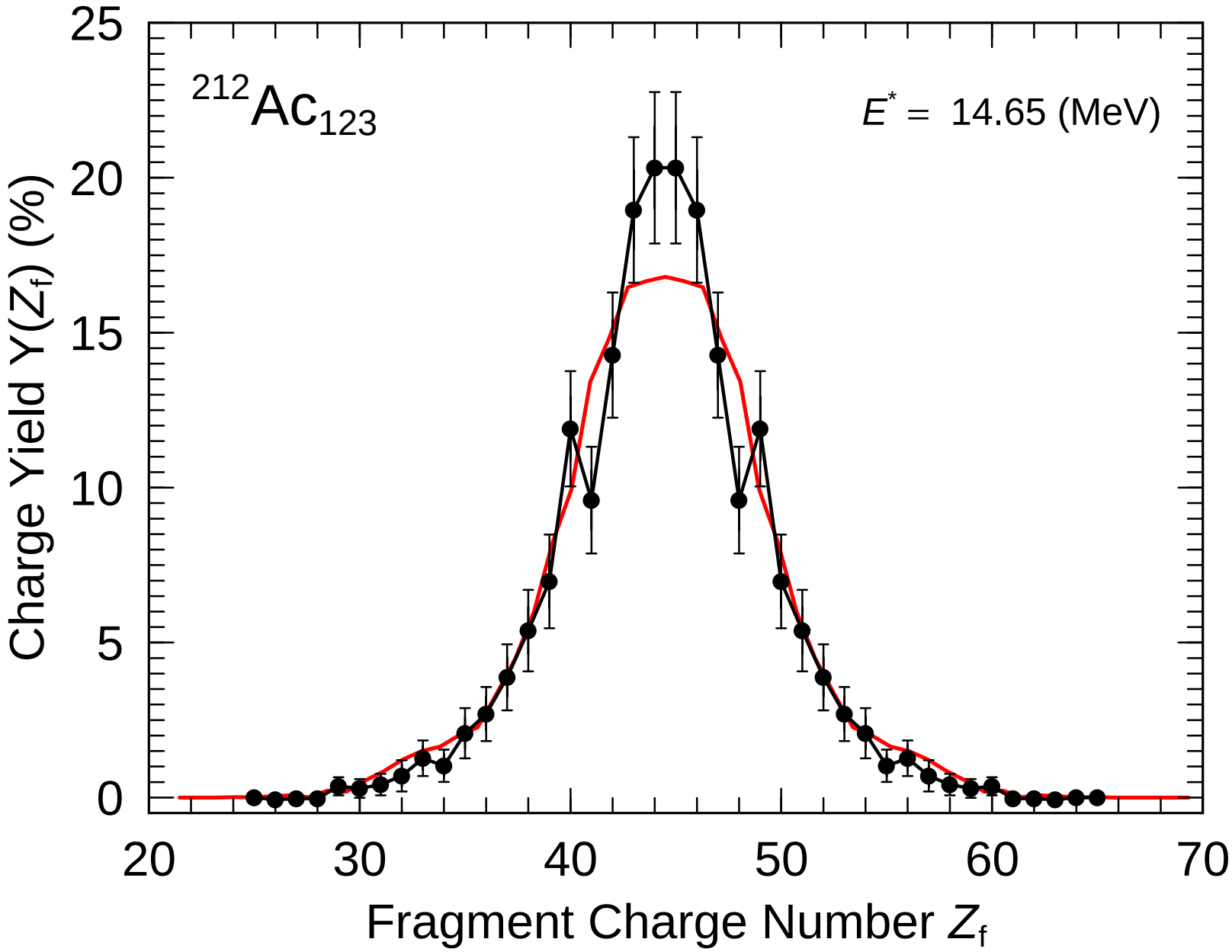
$^{212}Ac_{123}$
E^* = 14.65 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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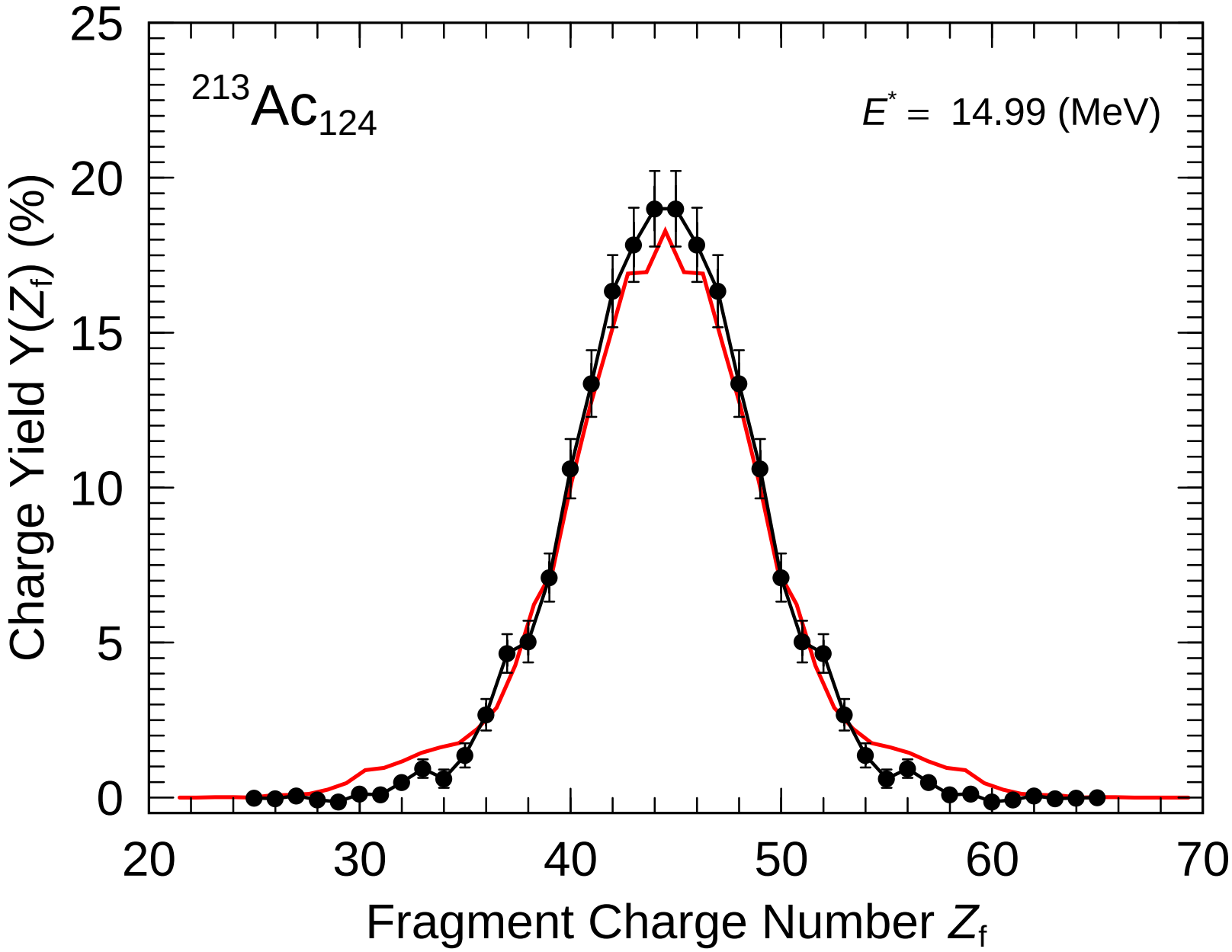
$^{213}Ac_{124}$
E^* = 14.99 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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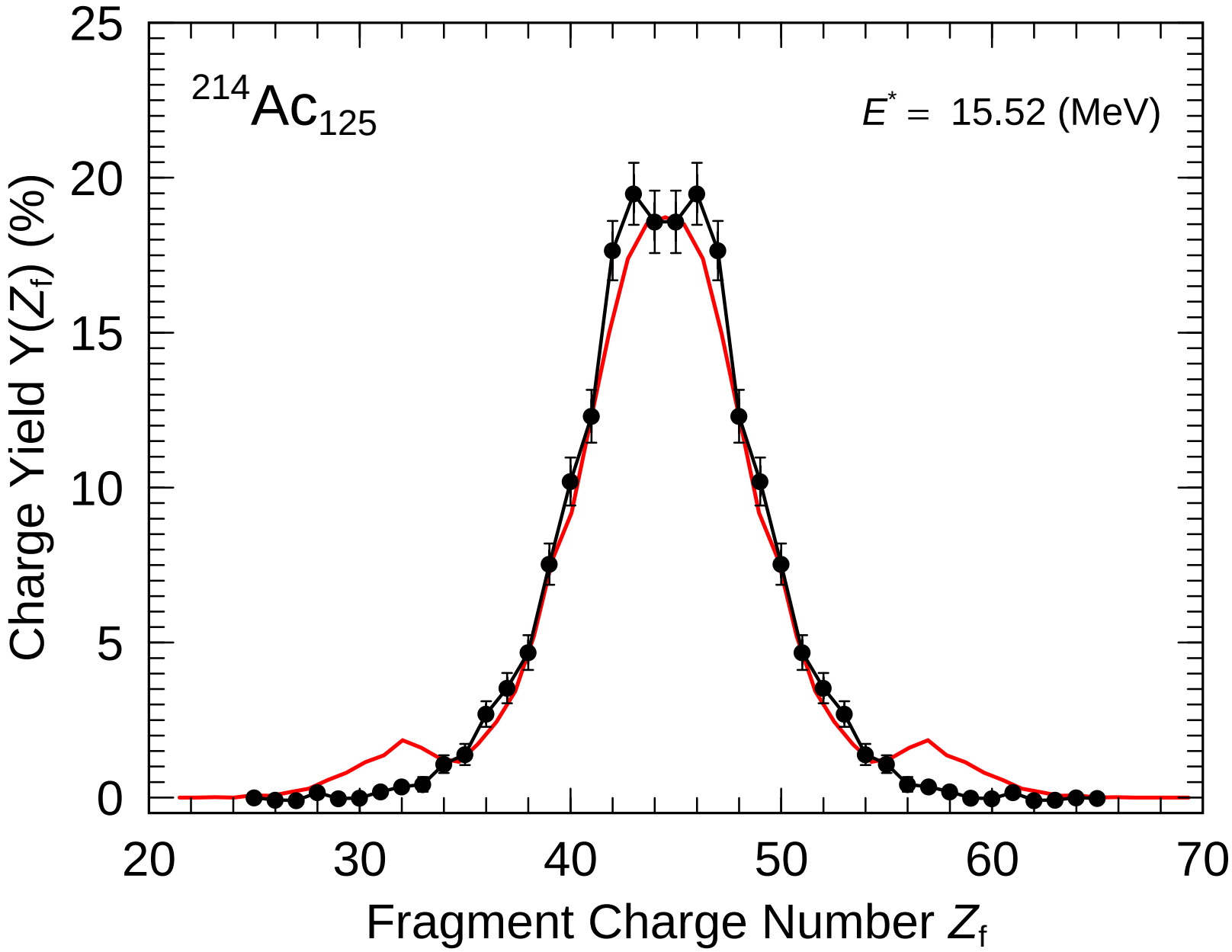
$^{214}Ac_{125}$
E^* = 15.52 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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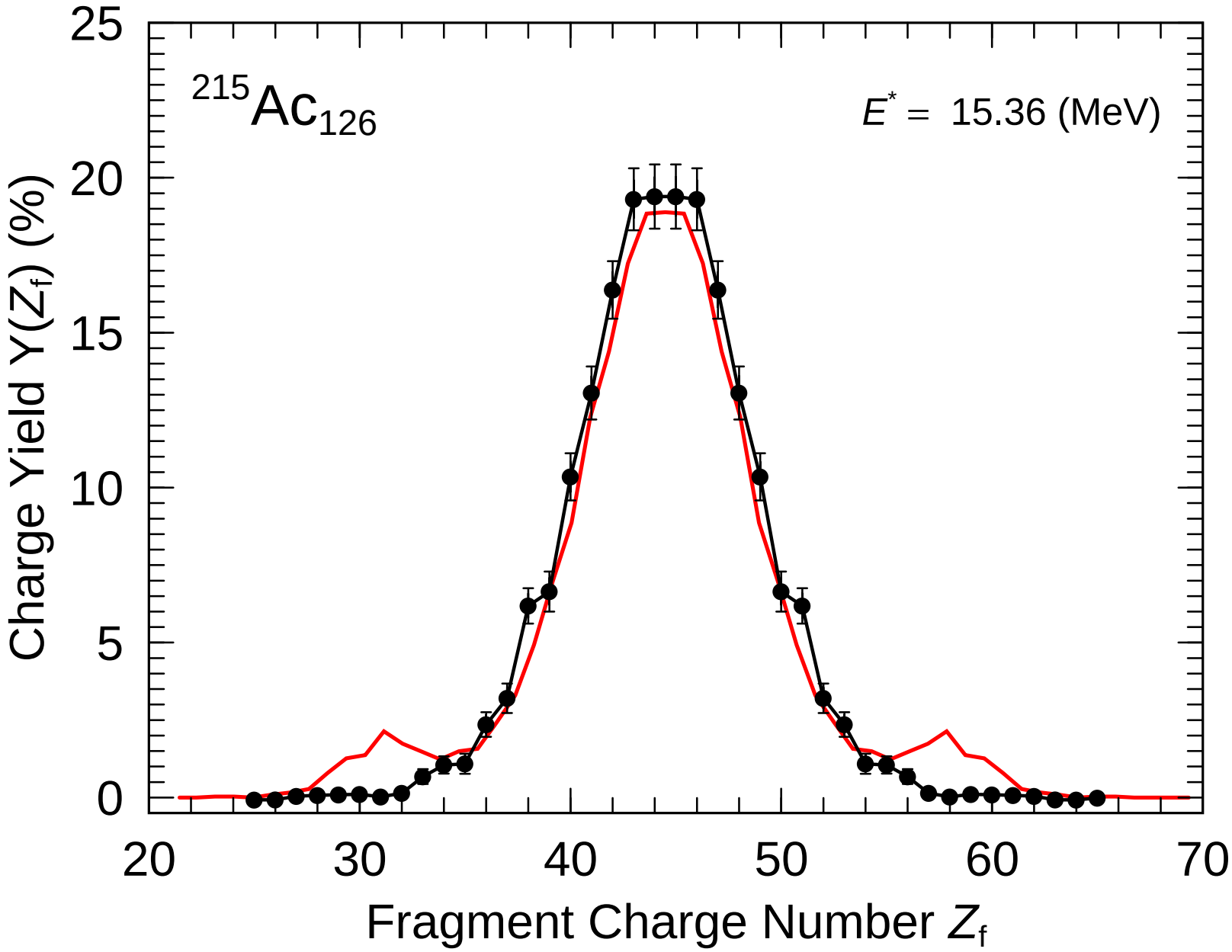
$^{215}Ac_{126}$
E^* = 15.36 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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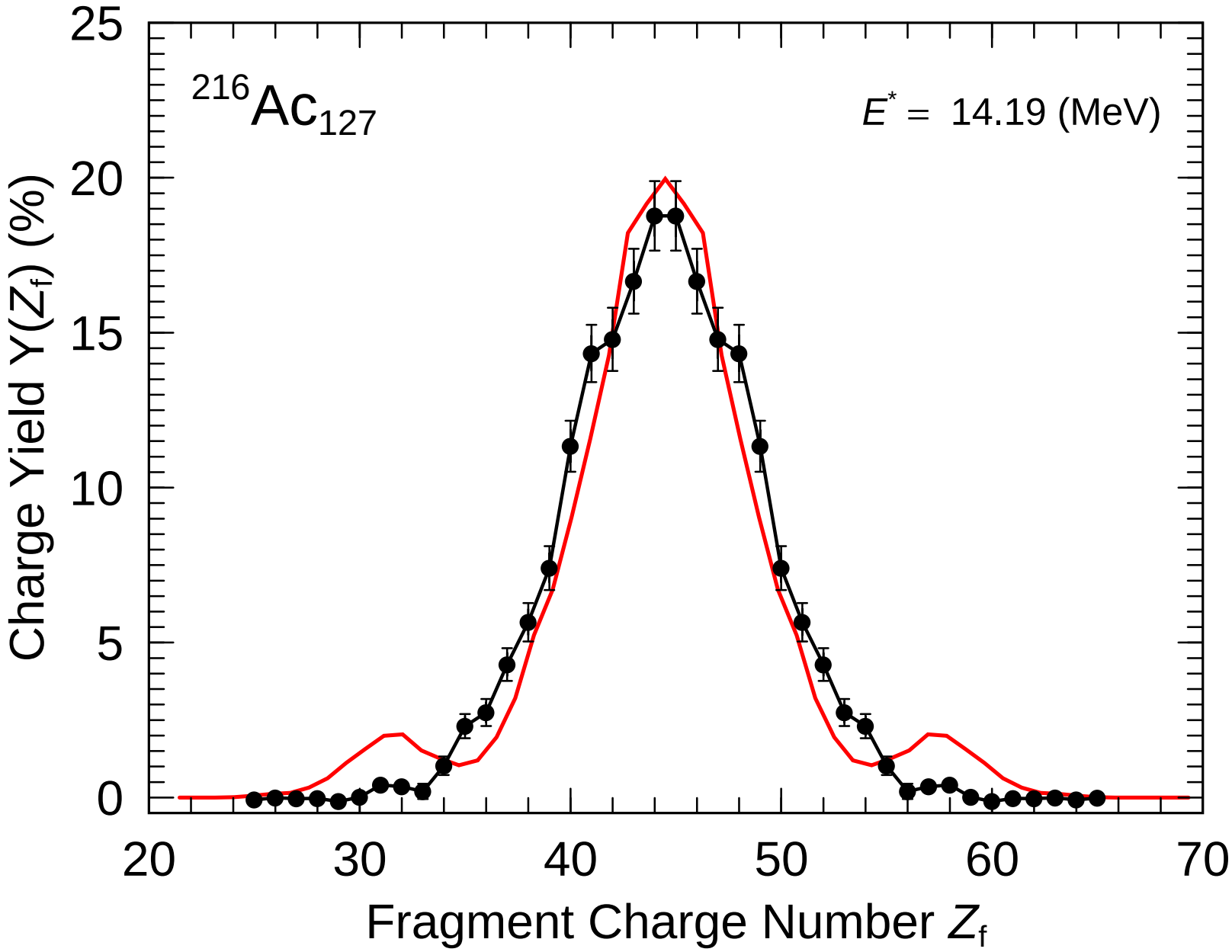
$^{216}Ac_{127}$
E^* = 14.19 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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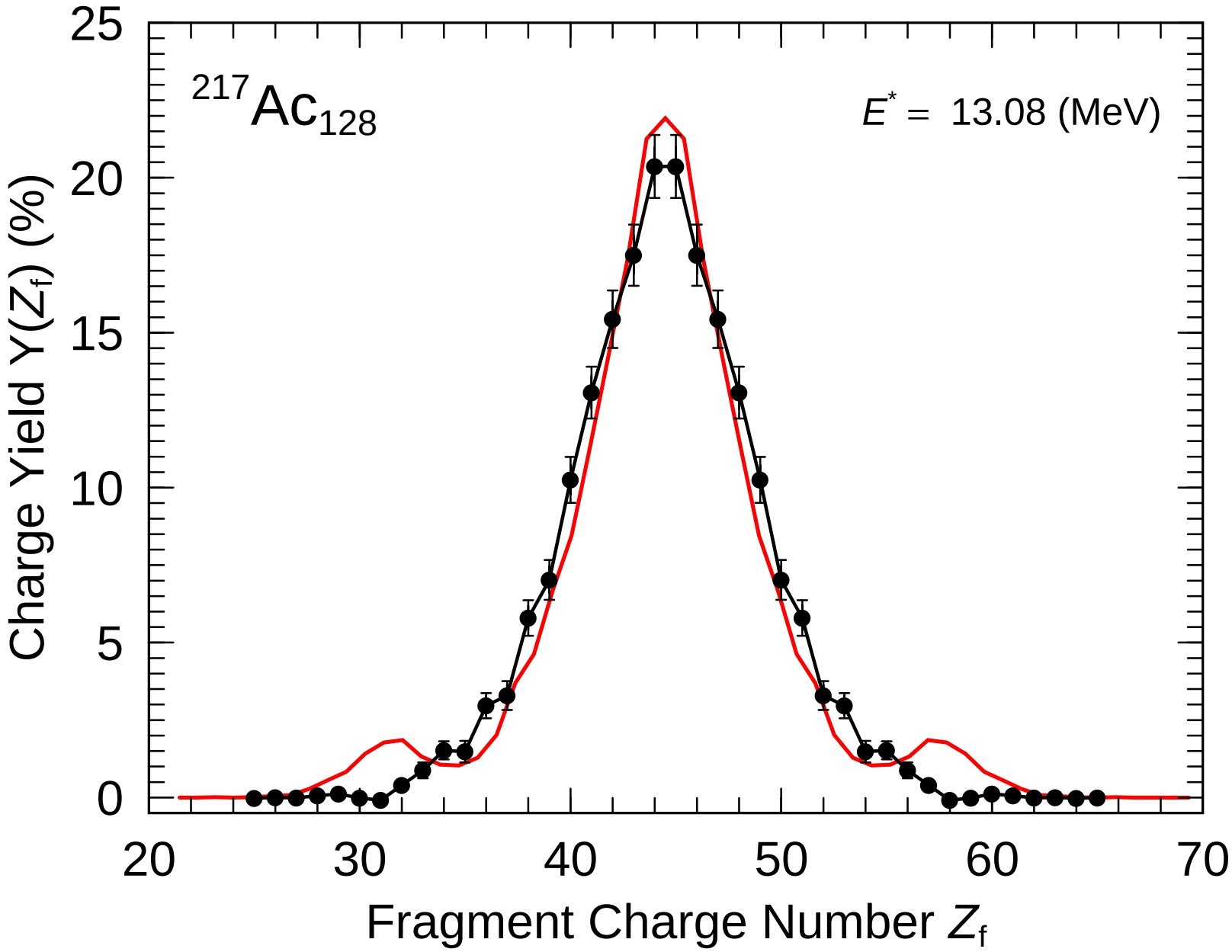
$^{217}Ac_{128}$
E^* = 13.08 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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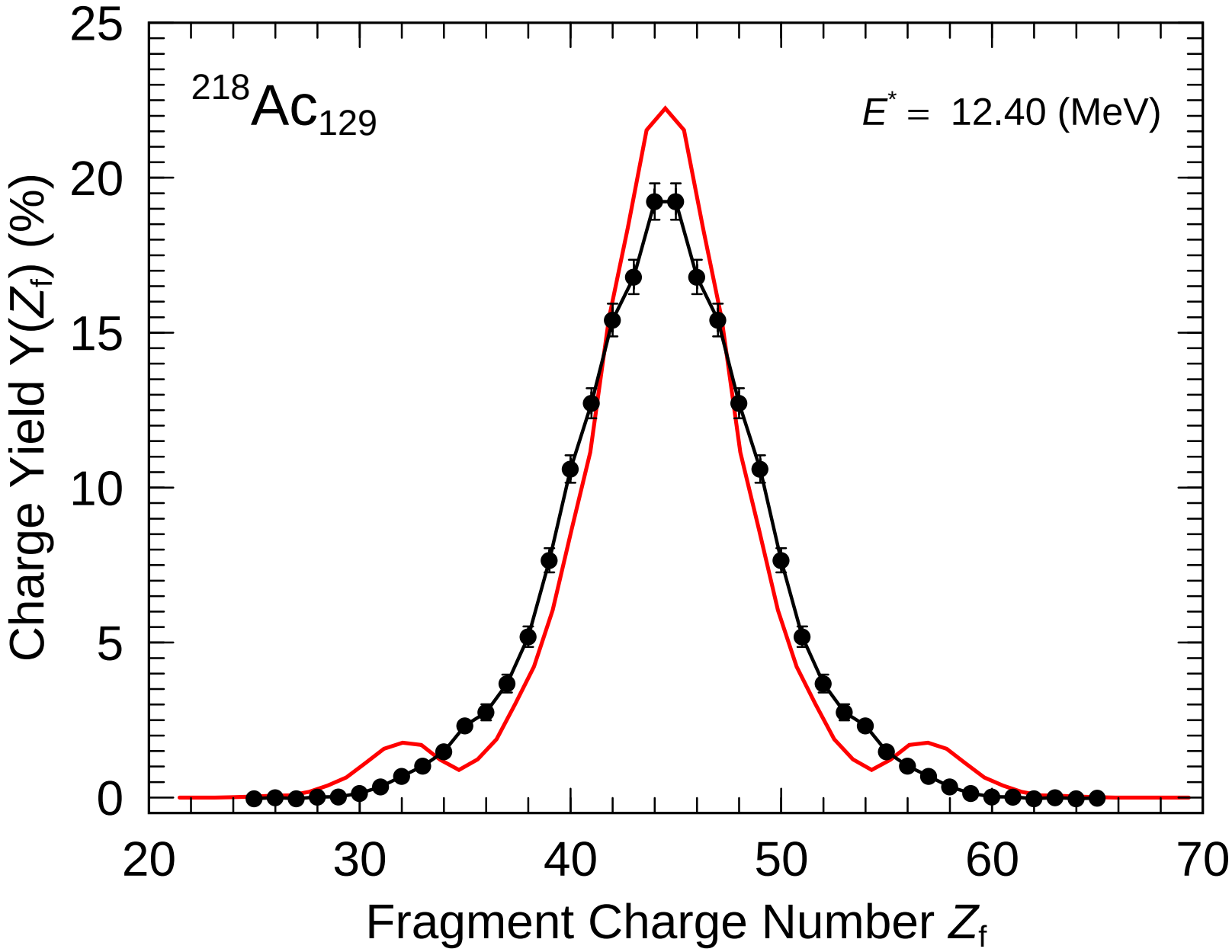
$^{218}Ac_{129}$
E^* = 12.40 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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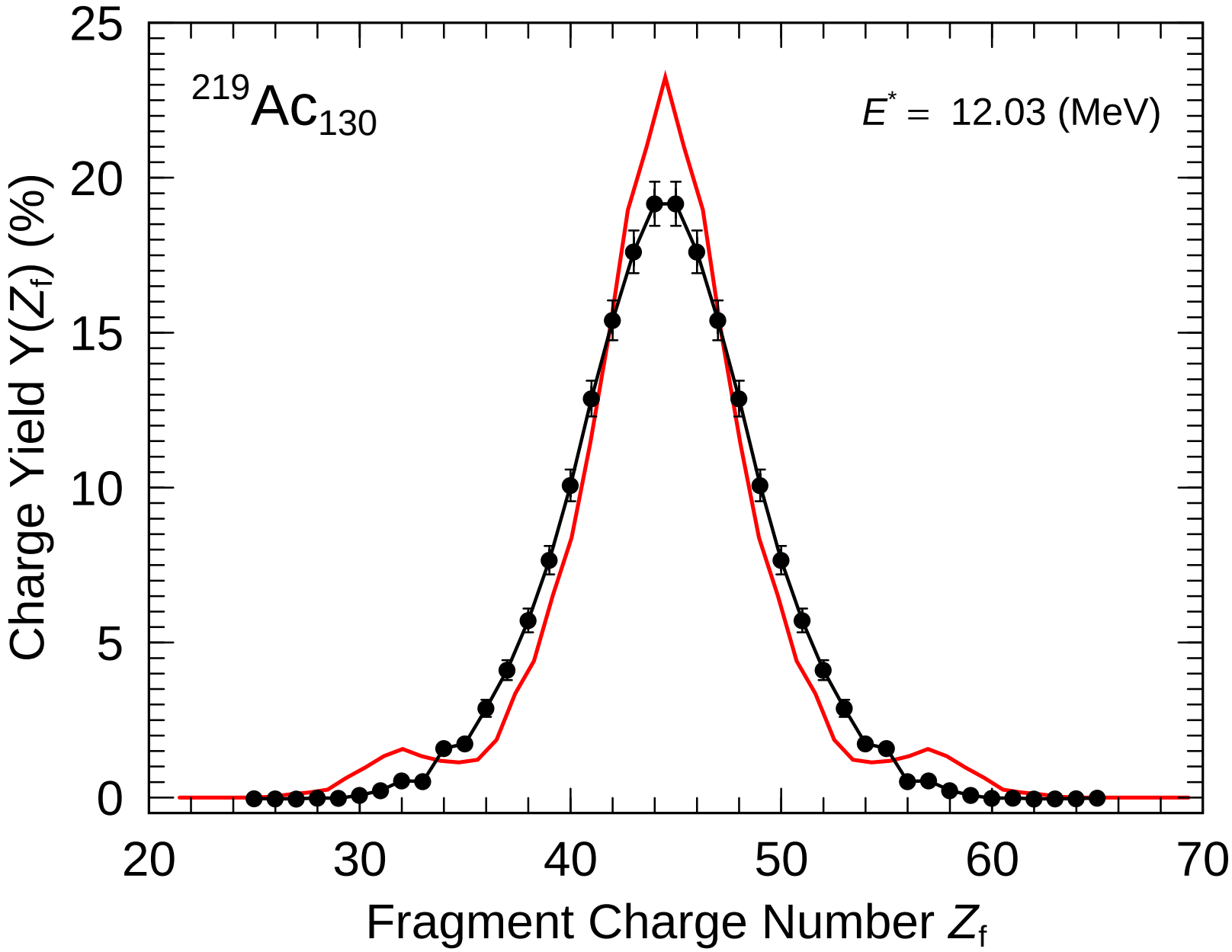
$^{219}Ac_{130}$
E^* = 12.03 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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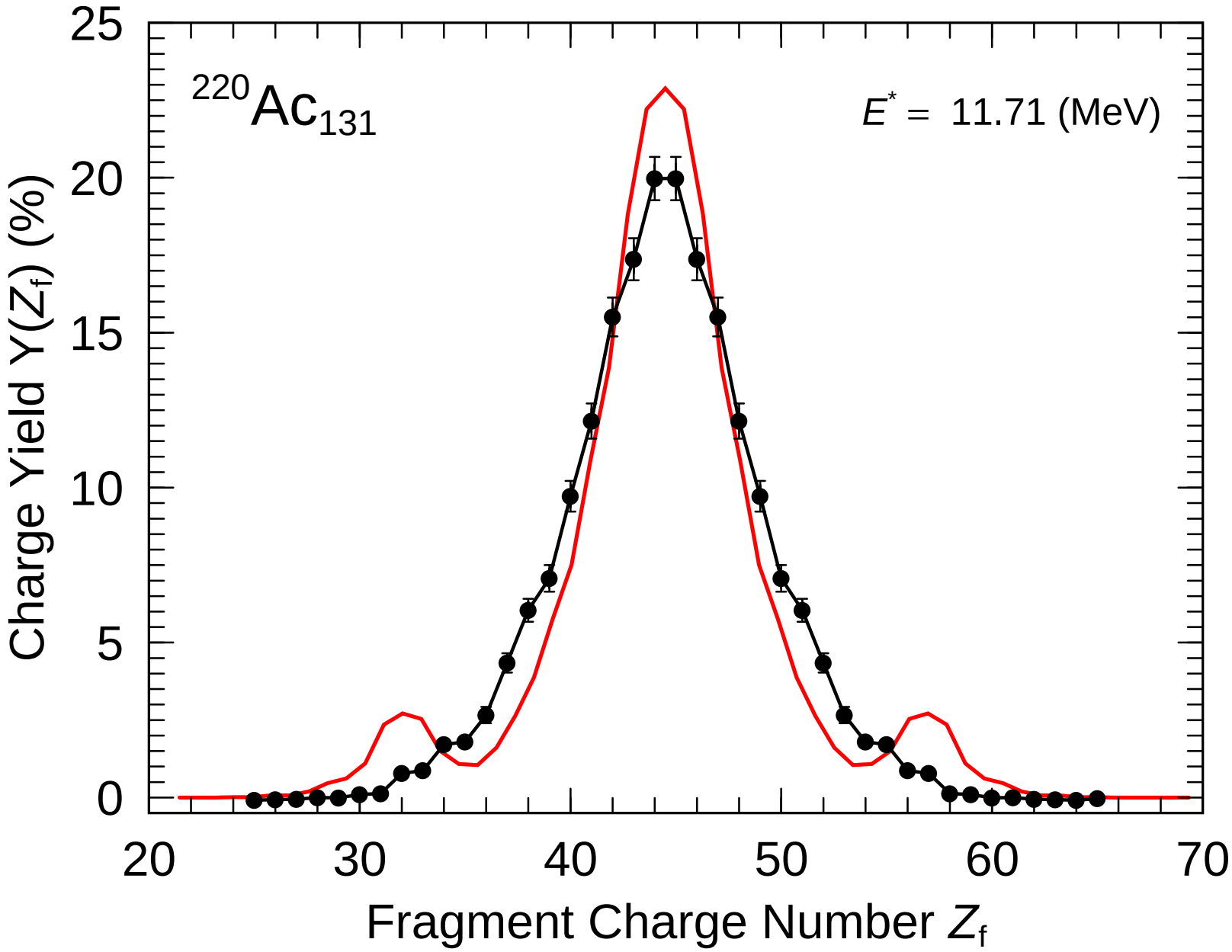
$^{220}Ac_{131}$
E^* = 11.71 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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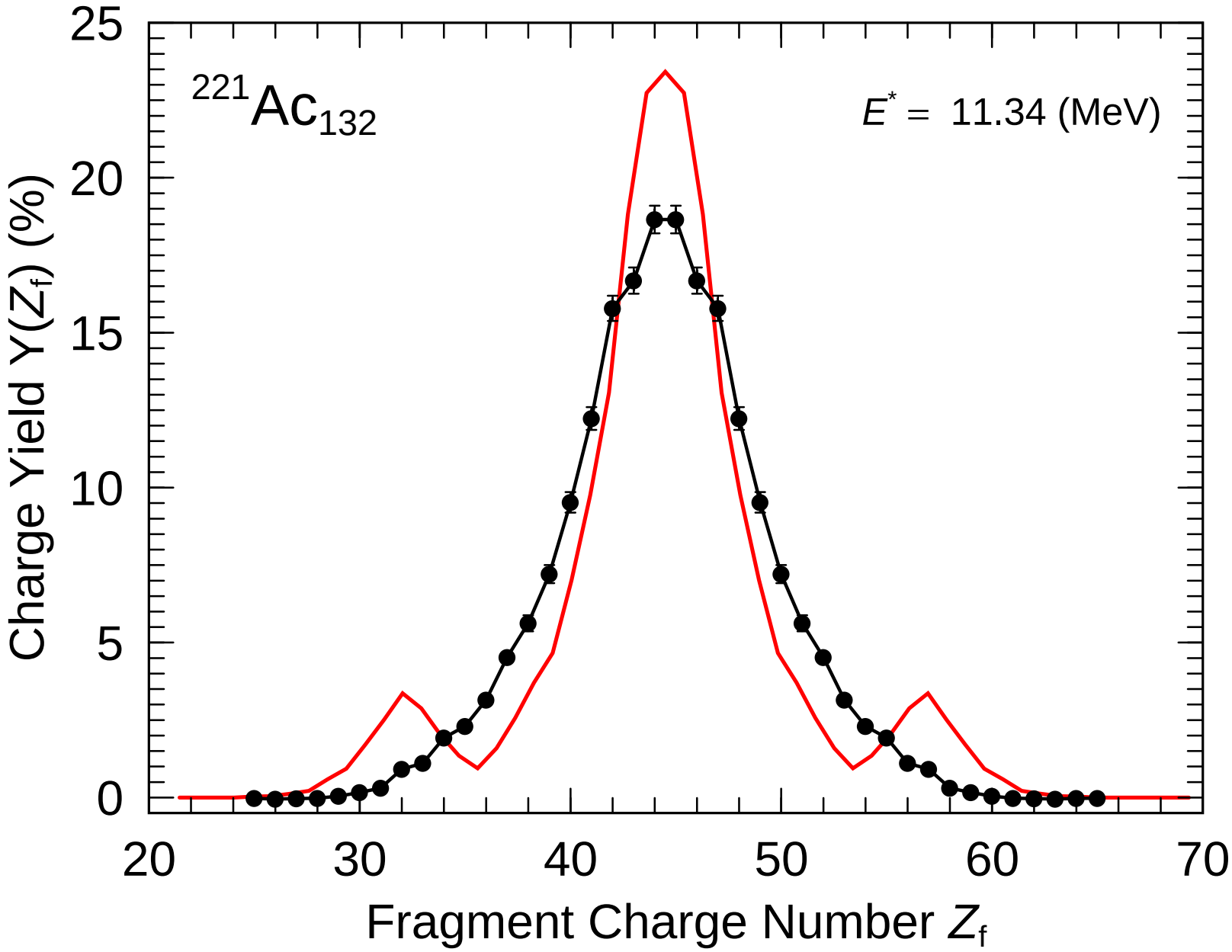
$^{221}Ac_{132}$
E^* = 11.34 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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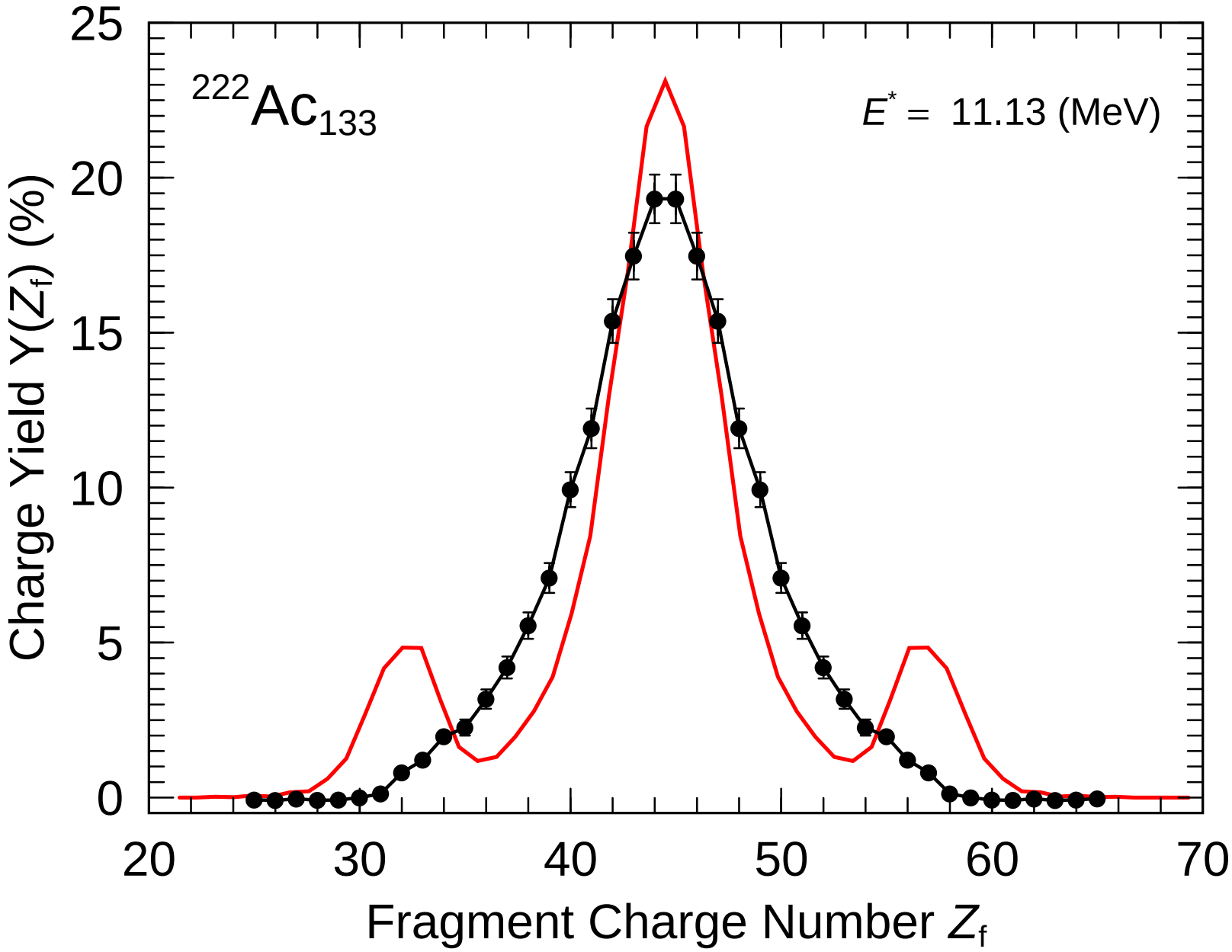
$^{222}Ac_{133}$
E^* = 11.13 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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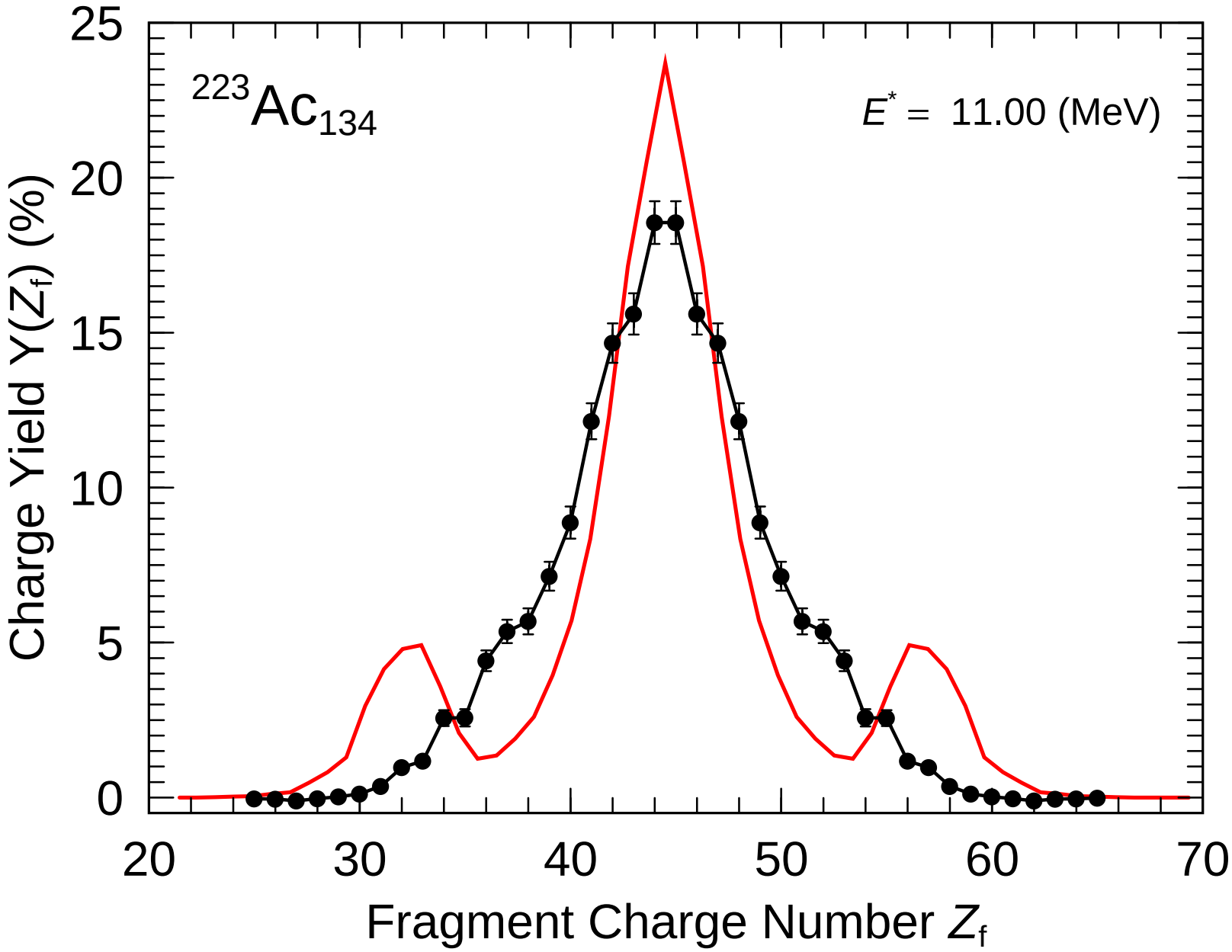
$^{223}Ac_{134}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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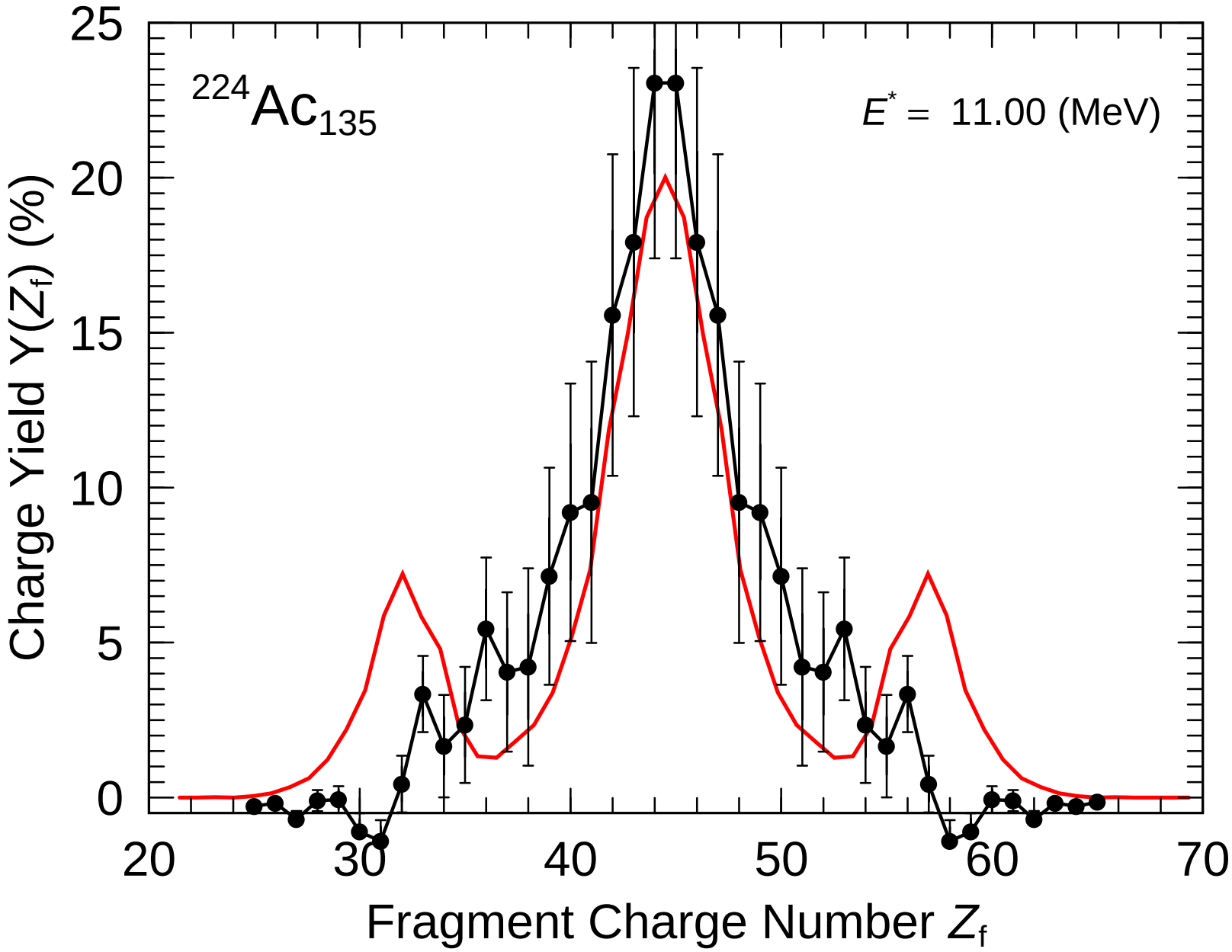
$^{224}Ac_{135}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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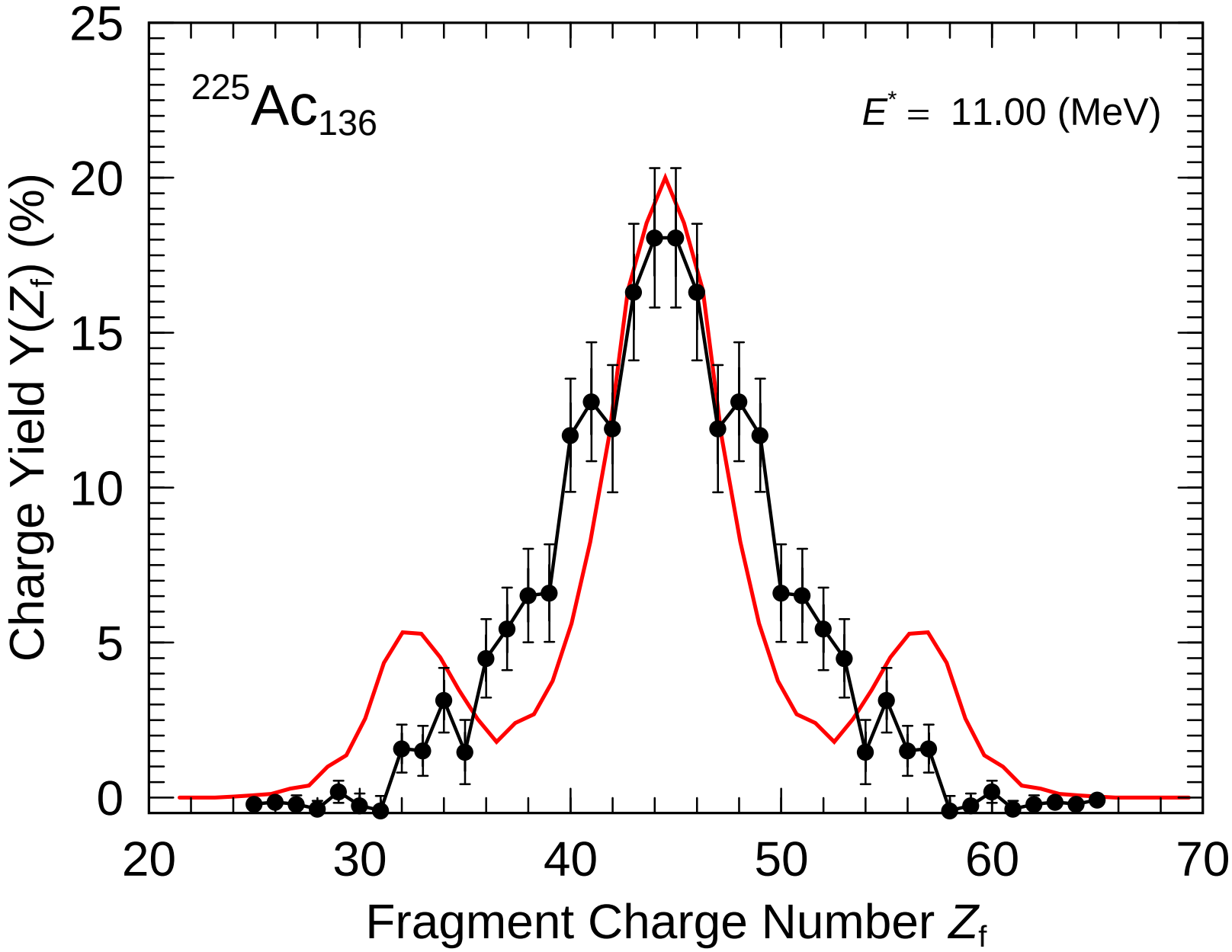
$^{225}Ac_{136}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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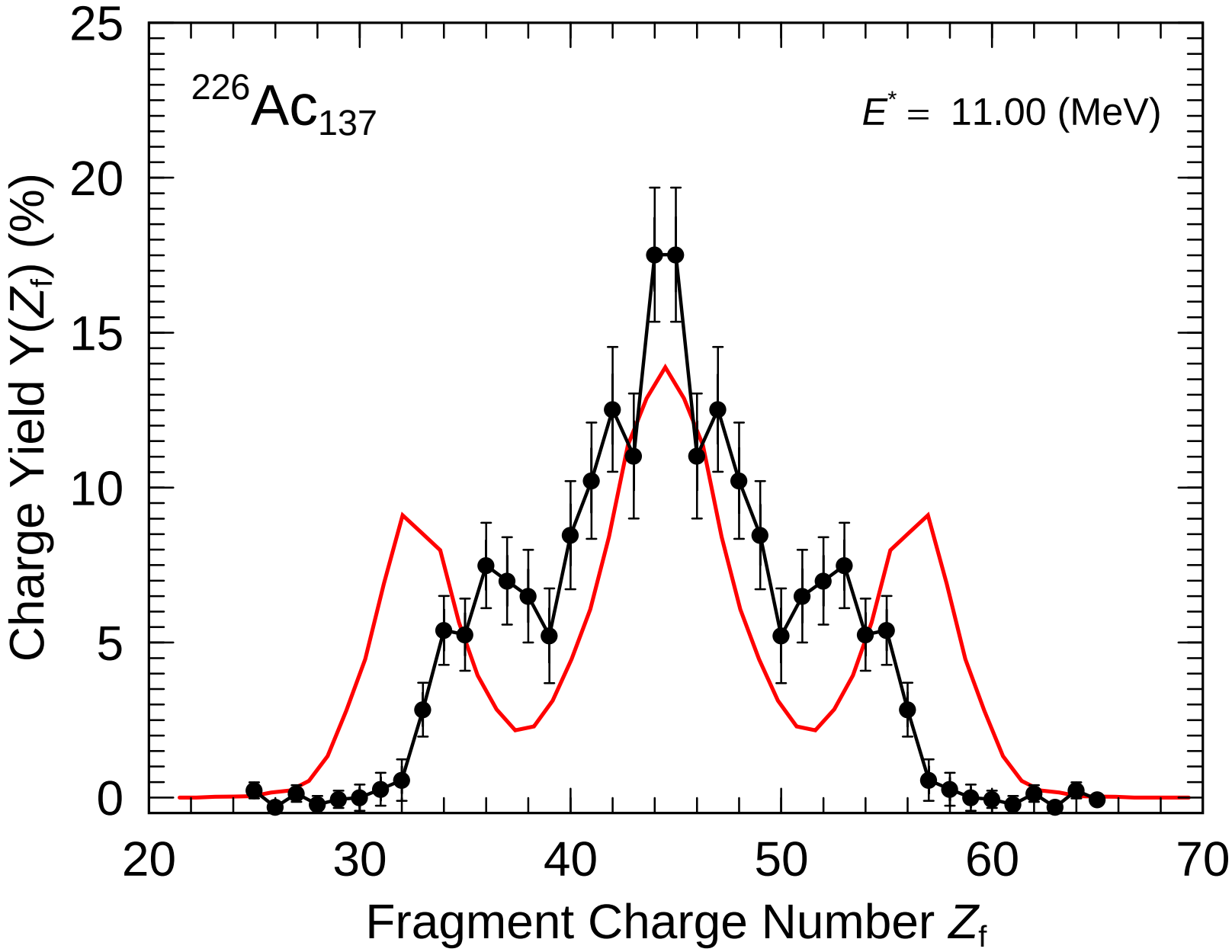
$^{226}Ac_{137}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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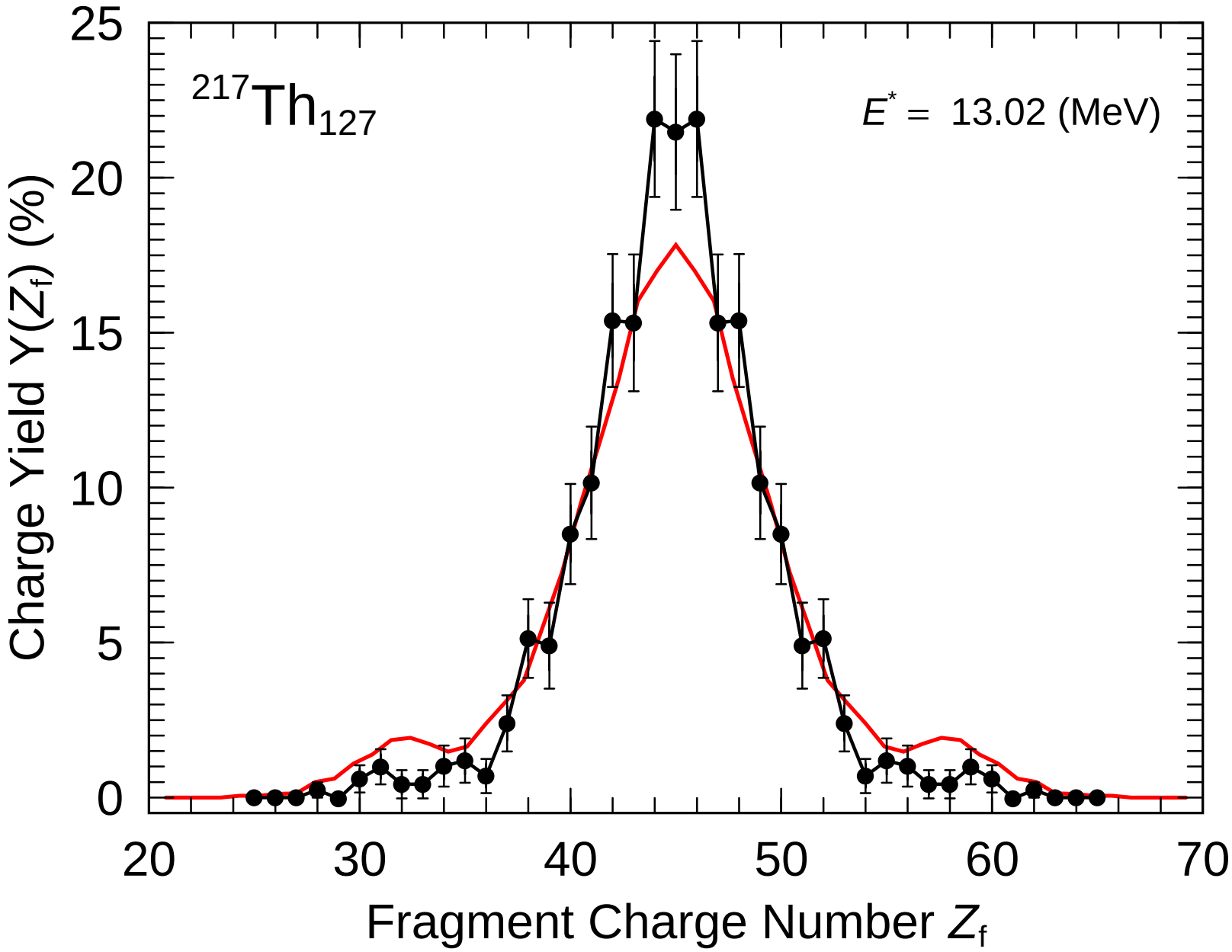
$^{217}Th_{127}$
E^* = 13.02 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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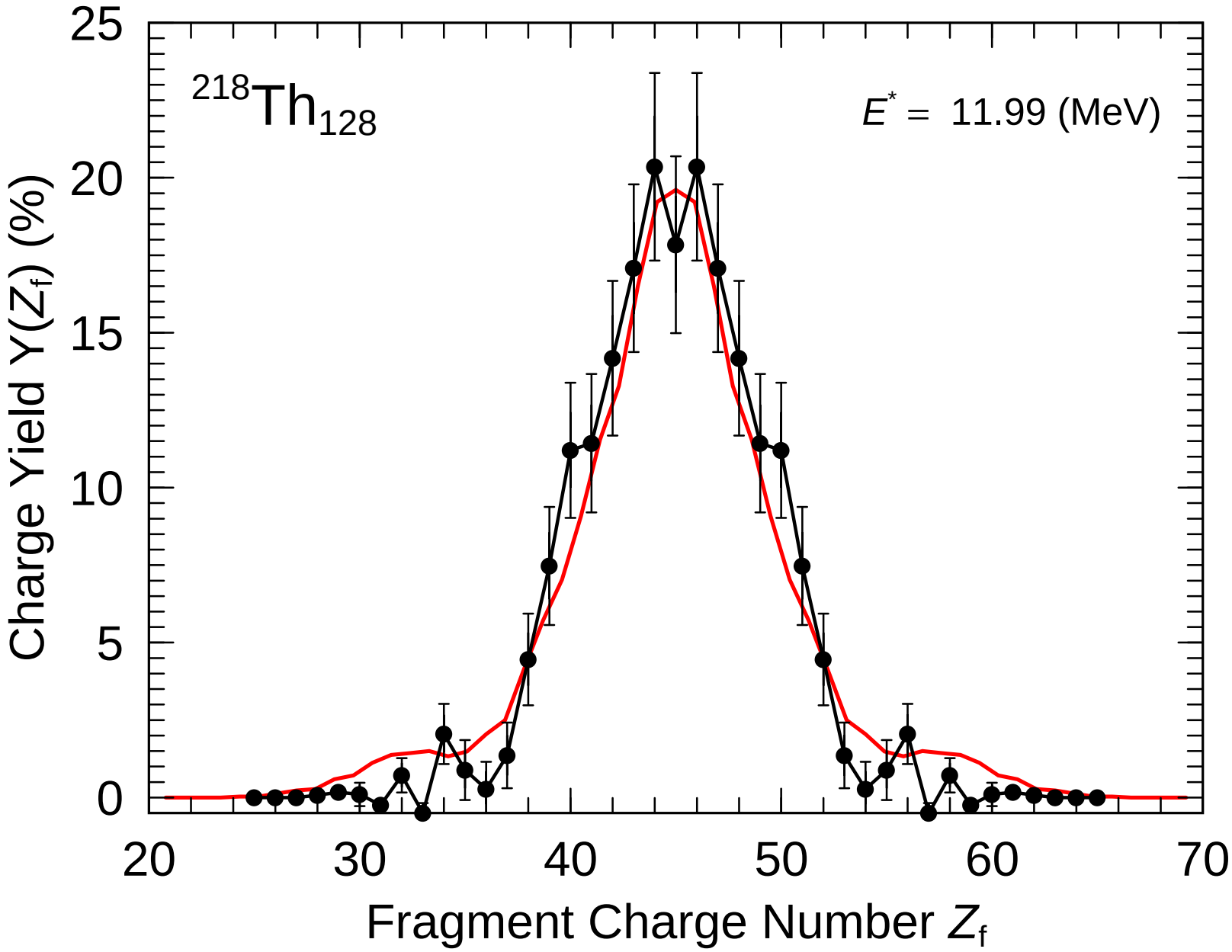
$^{218}Th_{128}$
E^* = 11.99 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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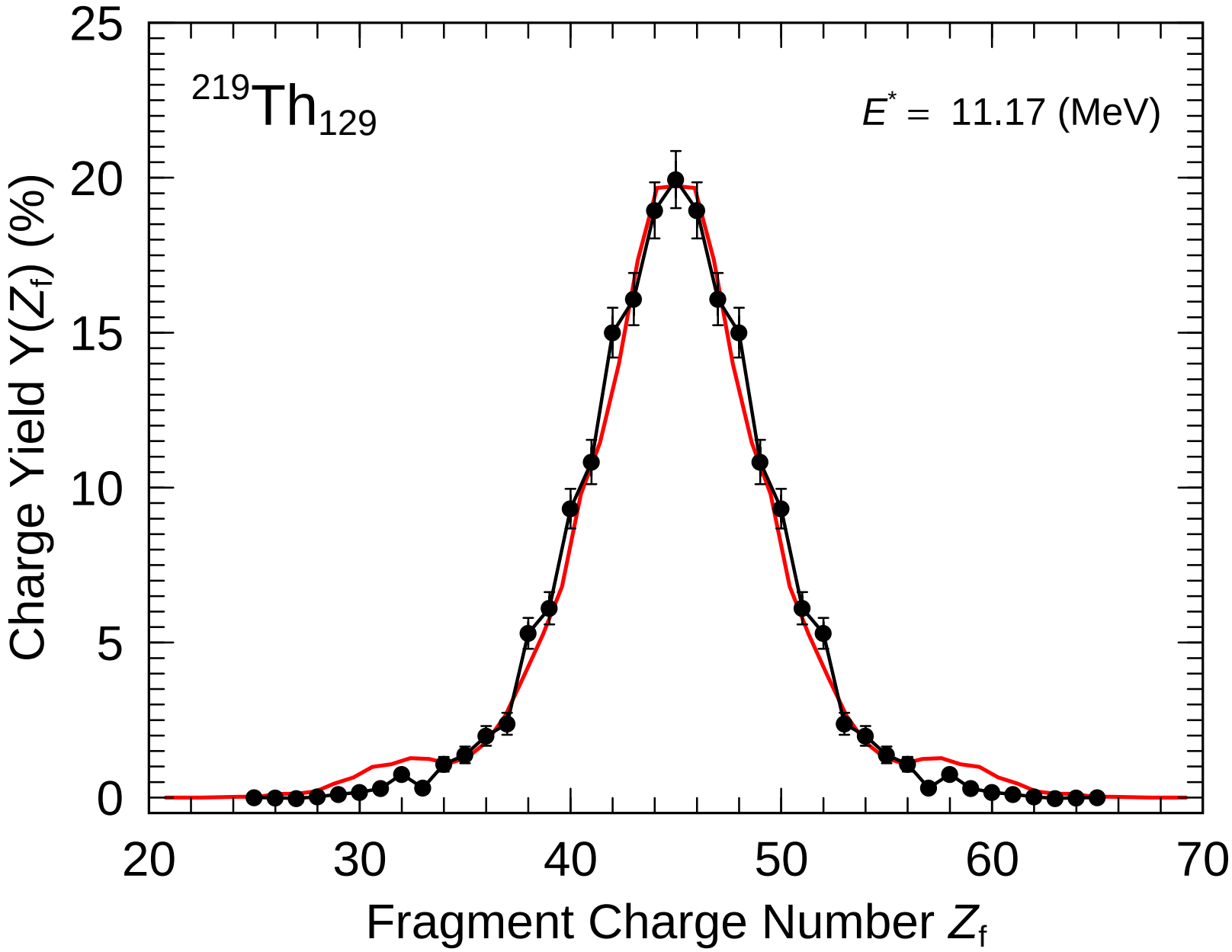
$^{219}Th_{129}$
E^* = 11.17 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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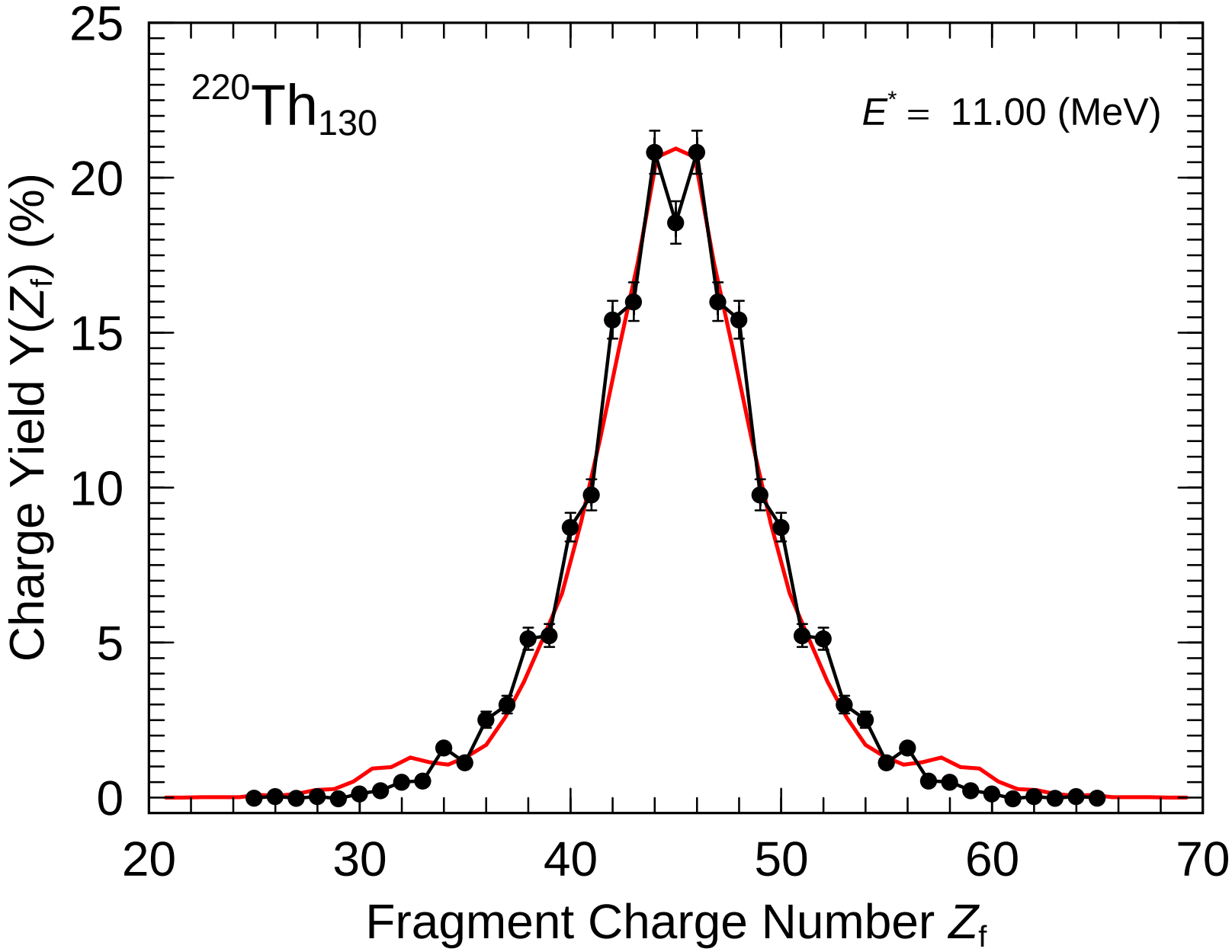
$^{220}Th_{130}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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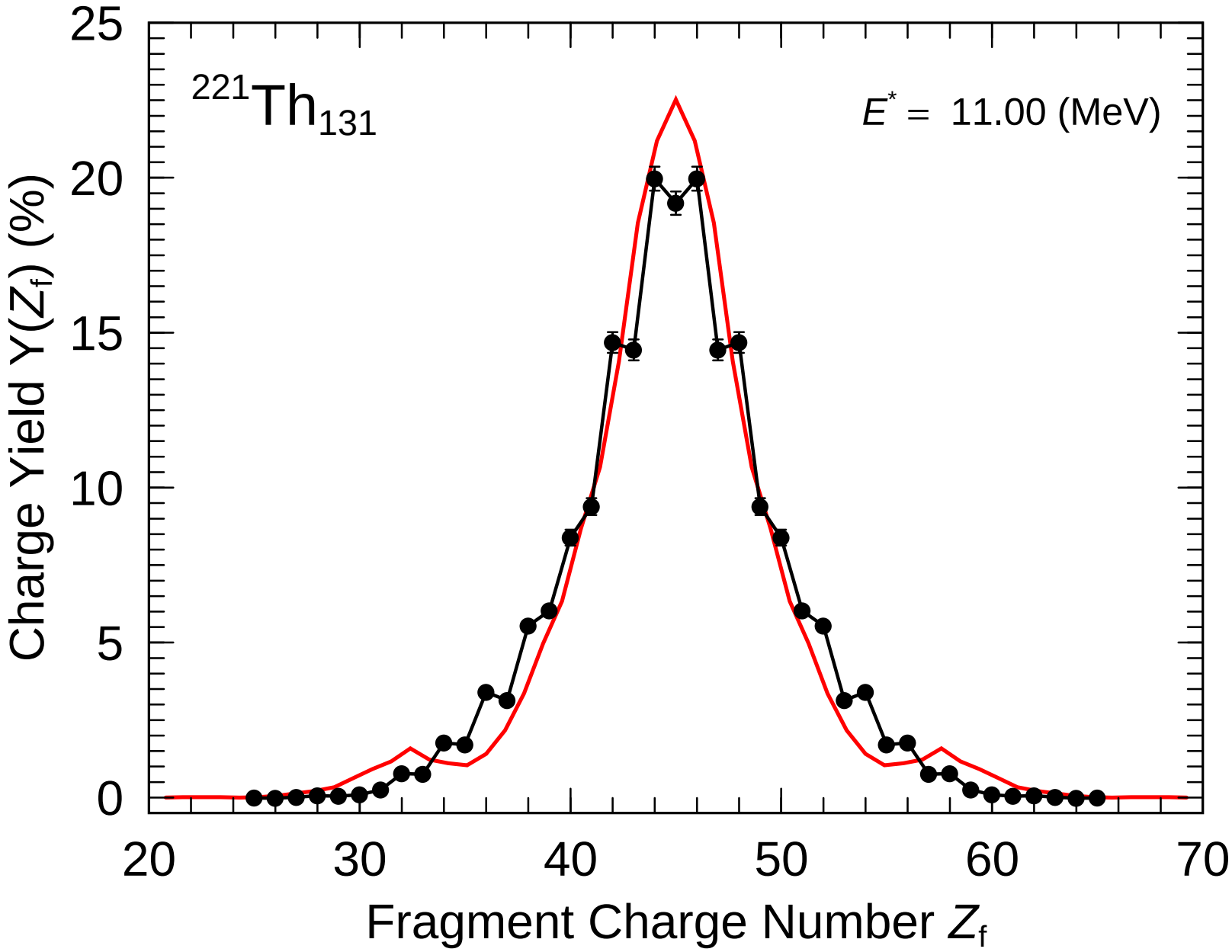
$^{221}Th_{131}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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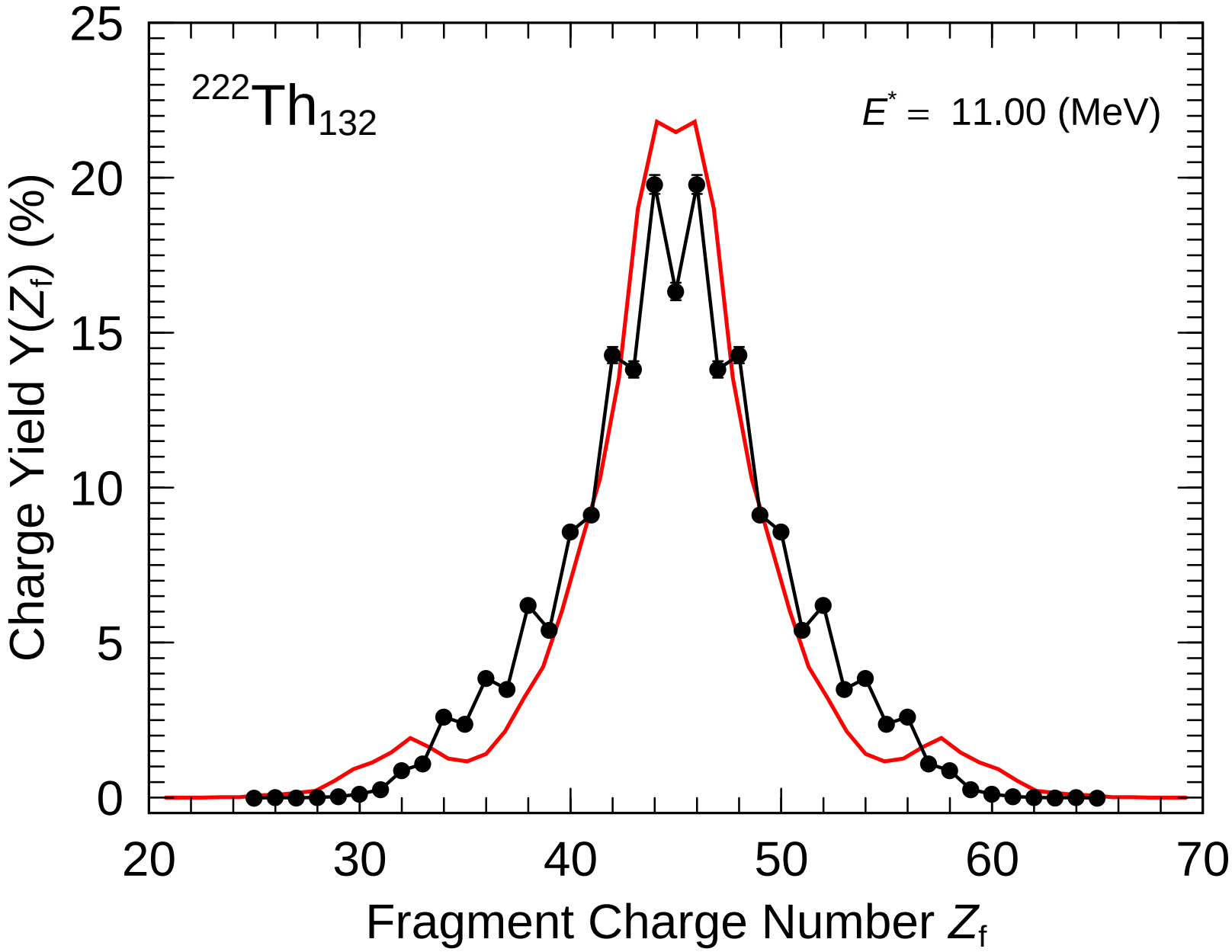
$^{222}Th_{132}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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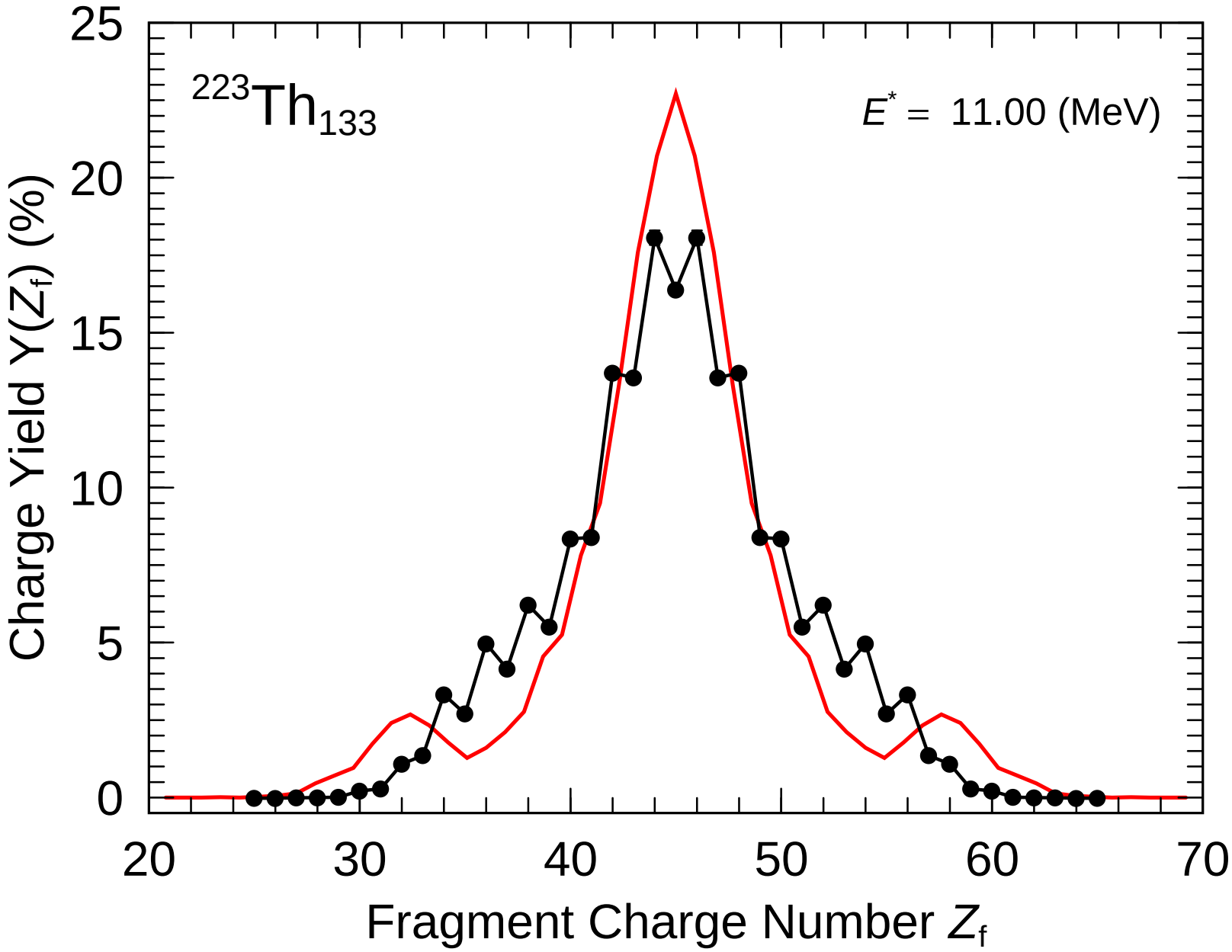
$^{223}Th_{133}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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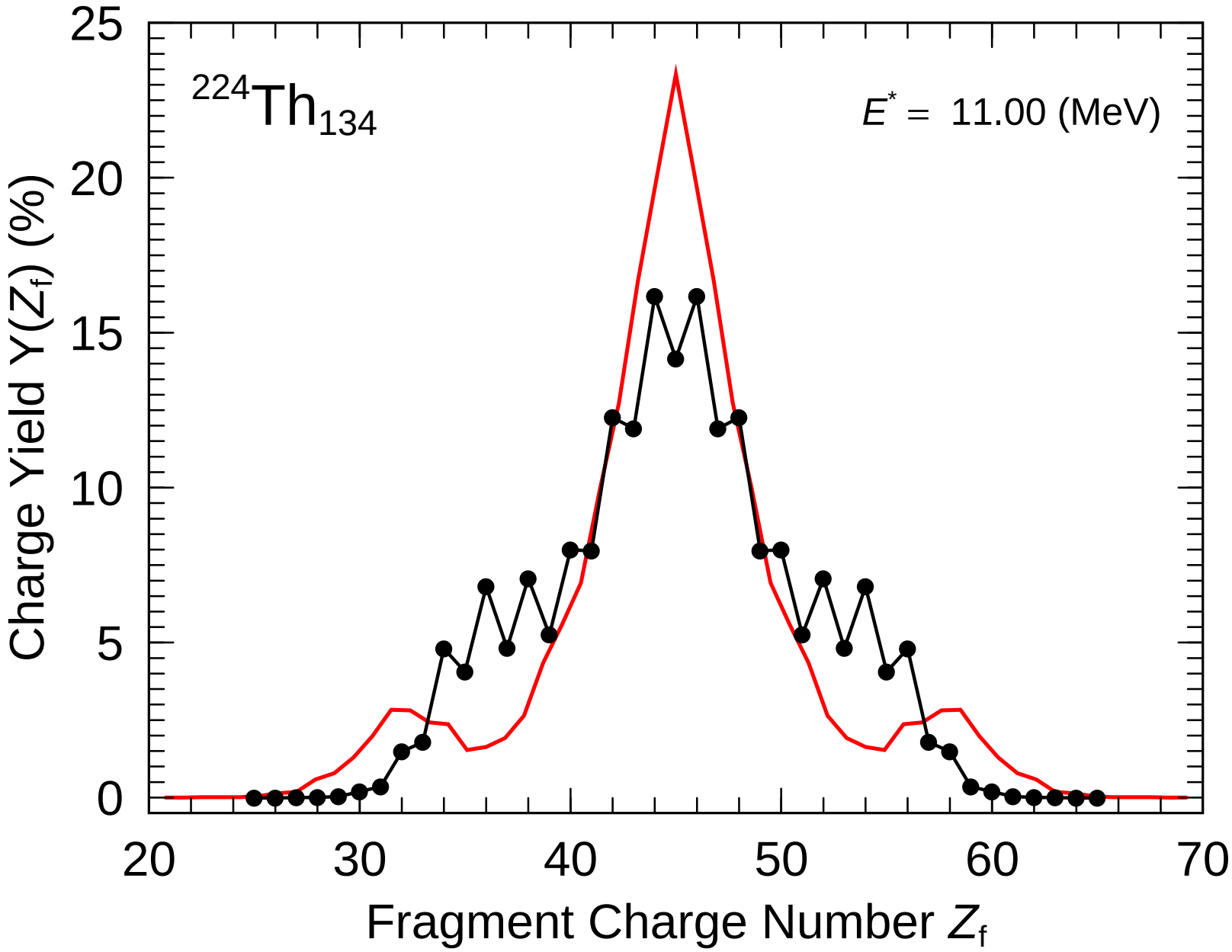
$^{224}Th_{134}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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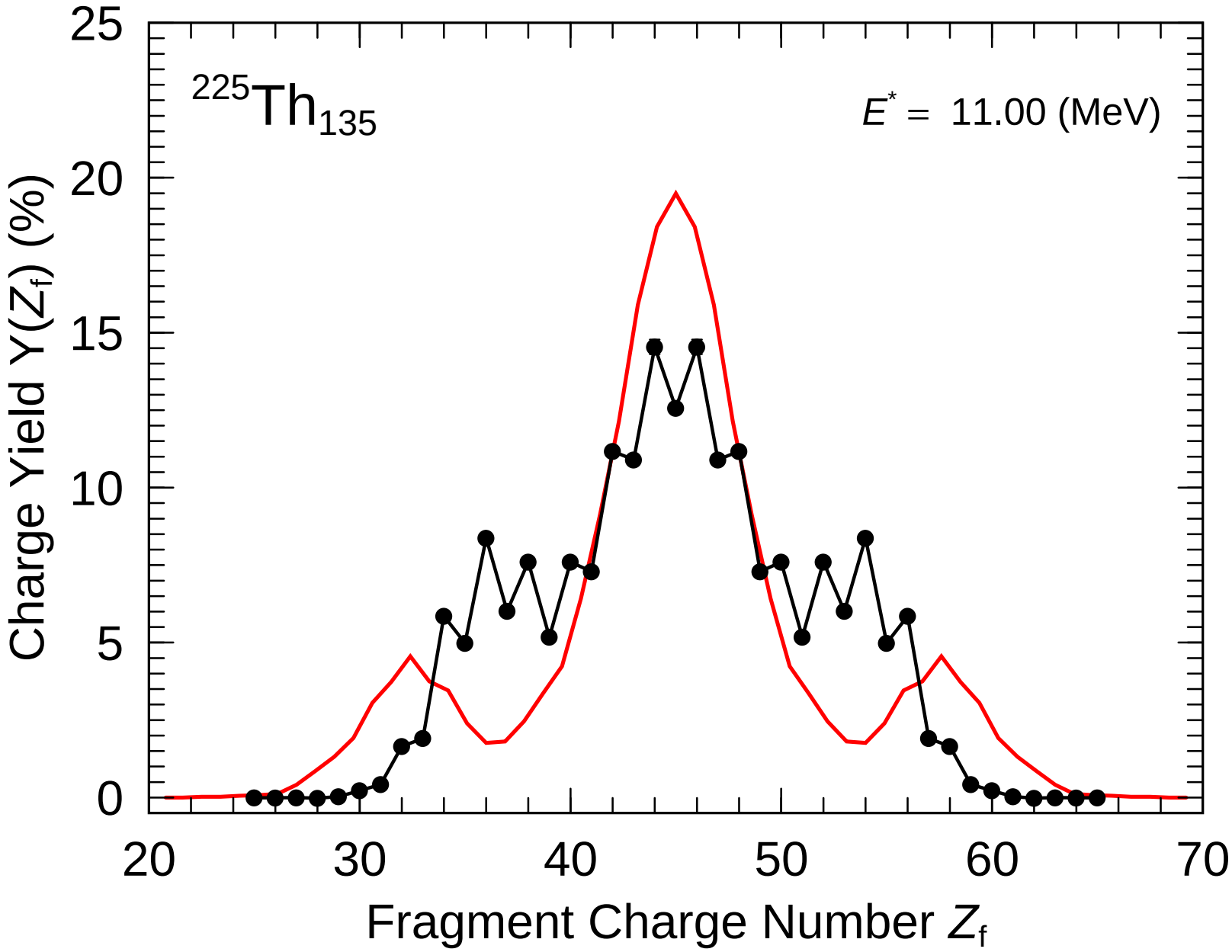
$^{225}Th_{135}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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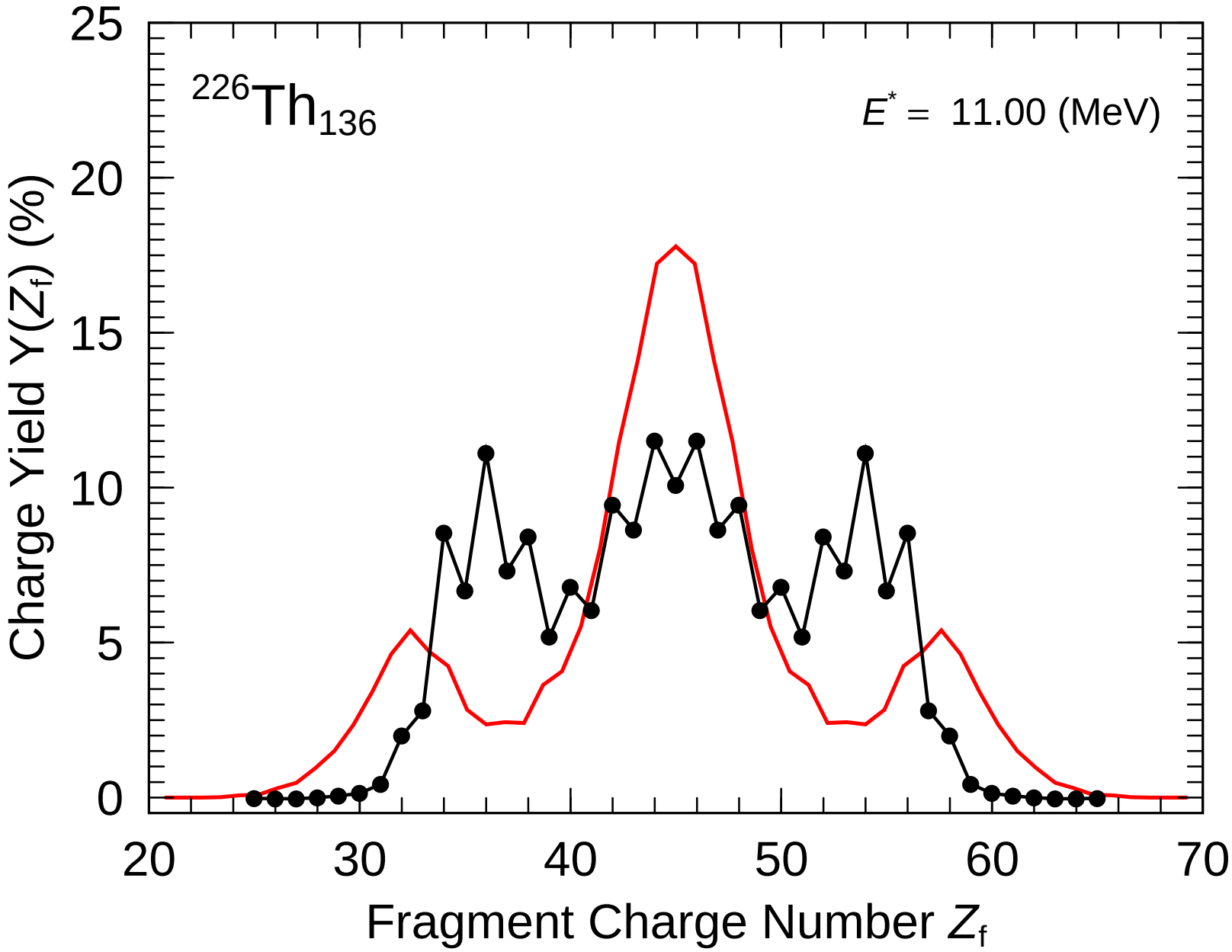
$^{226}Th_{136}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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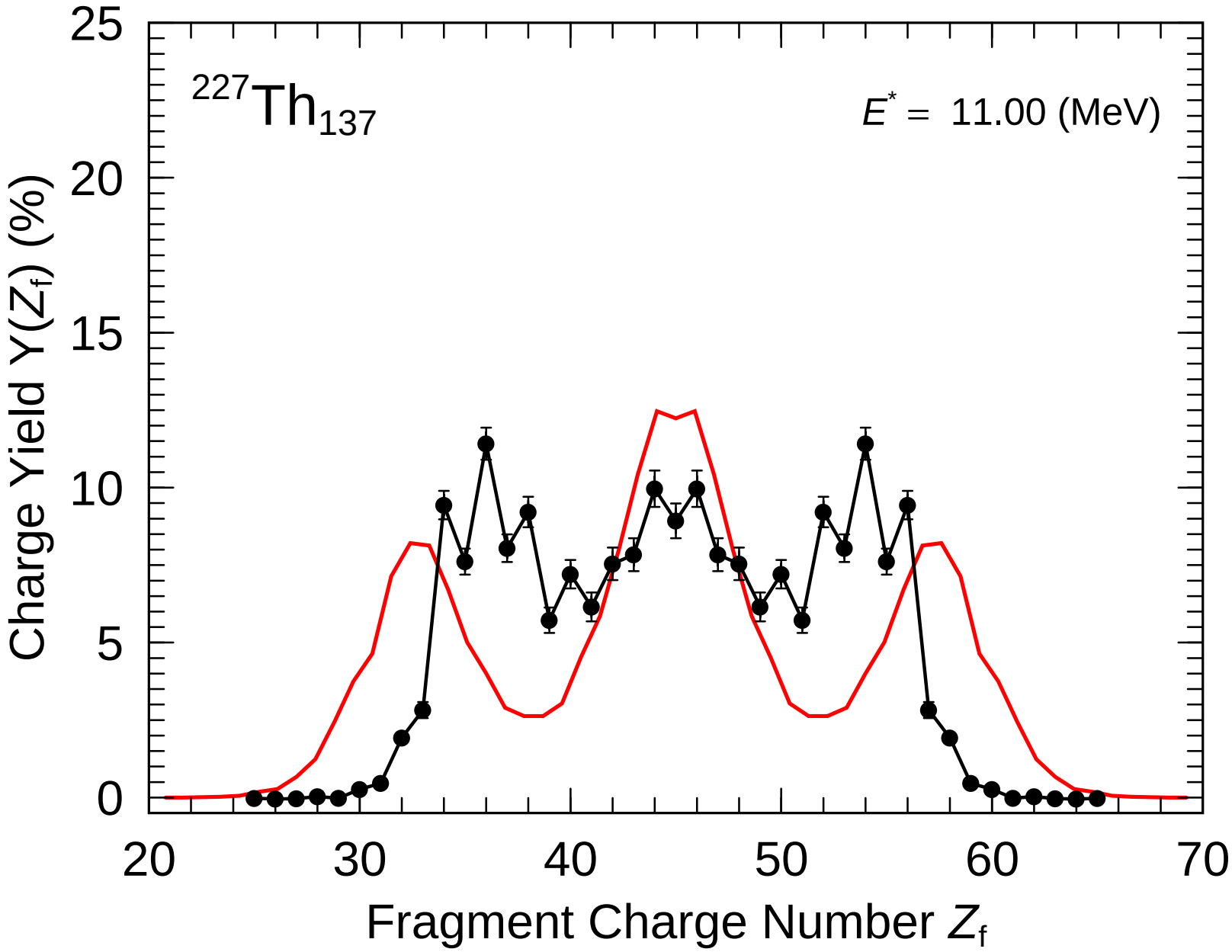
$^{227}Th_{137}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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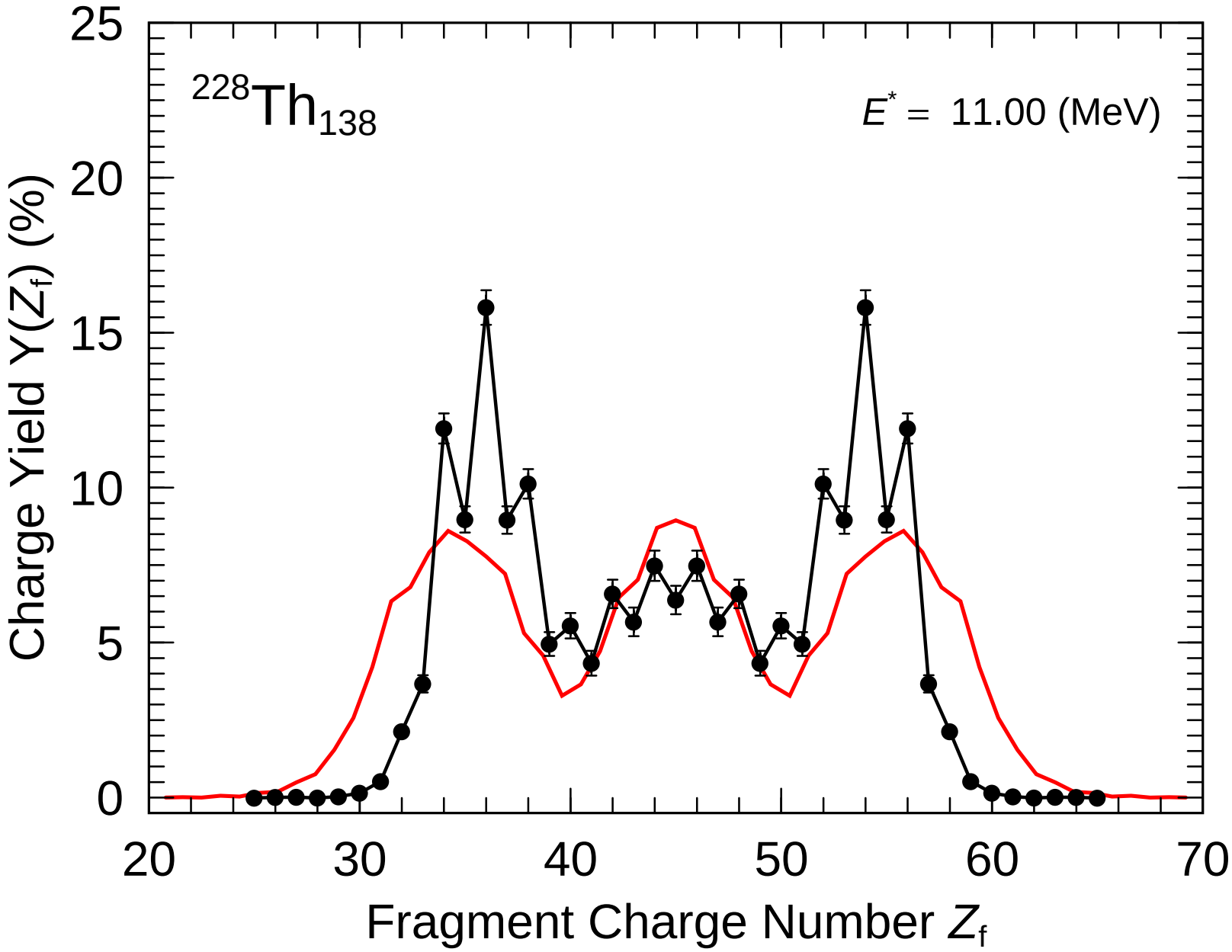
$^{228}Th_{138}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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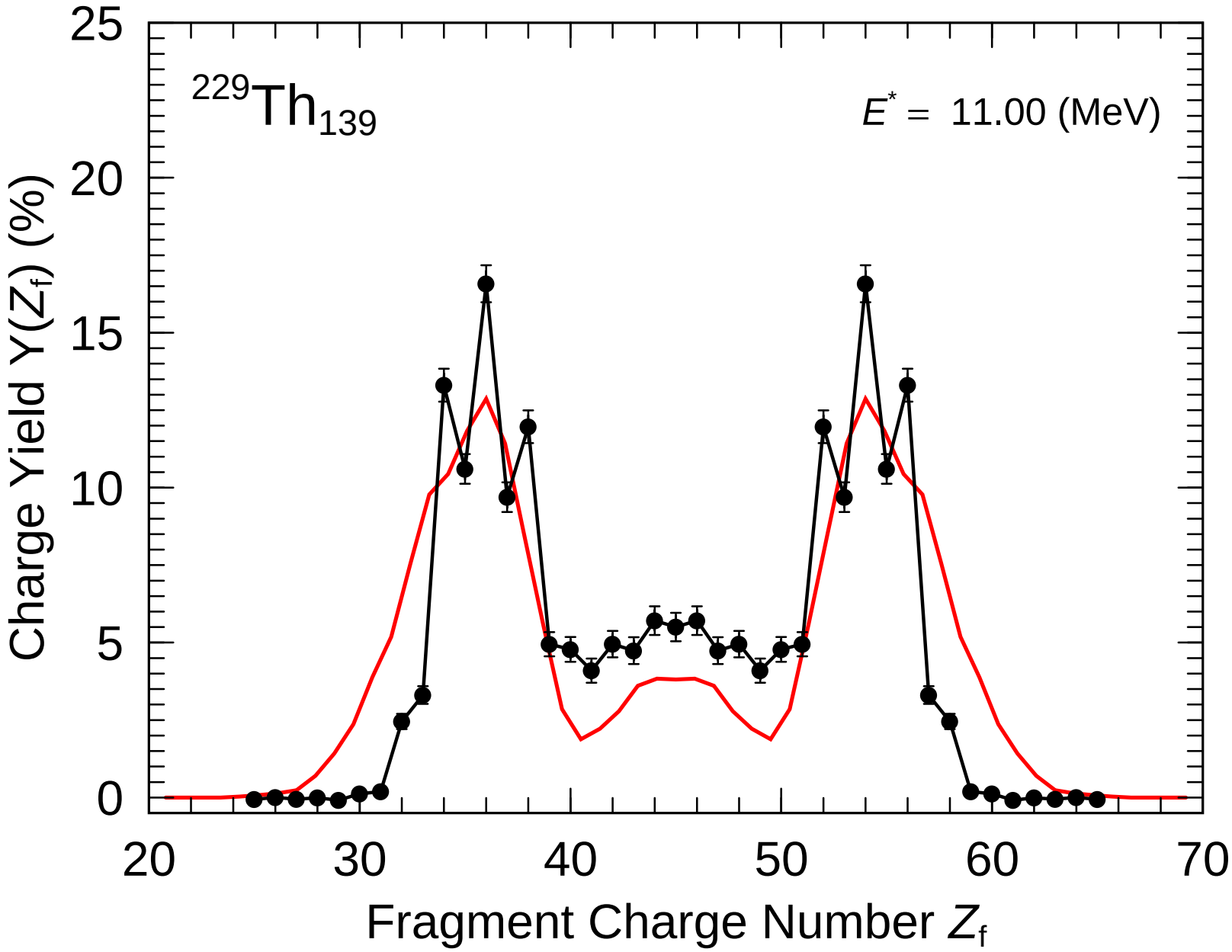
$^{229}Th_{139}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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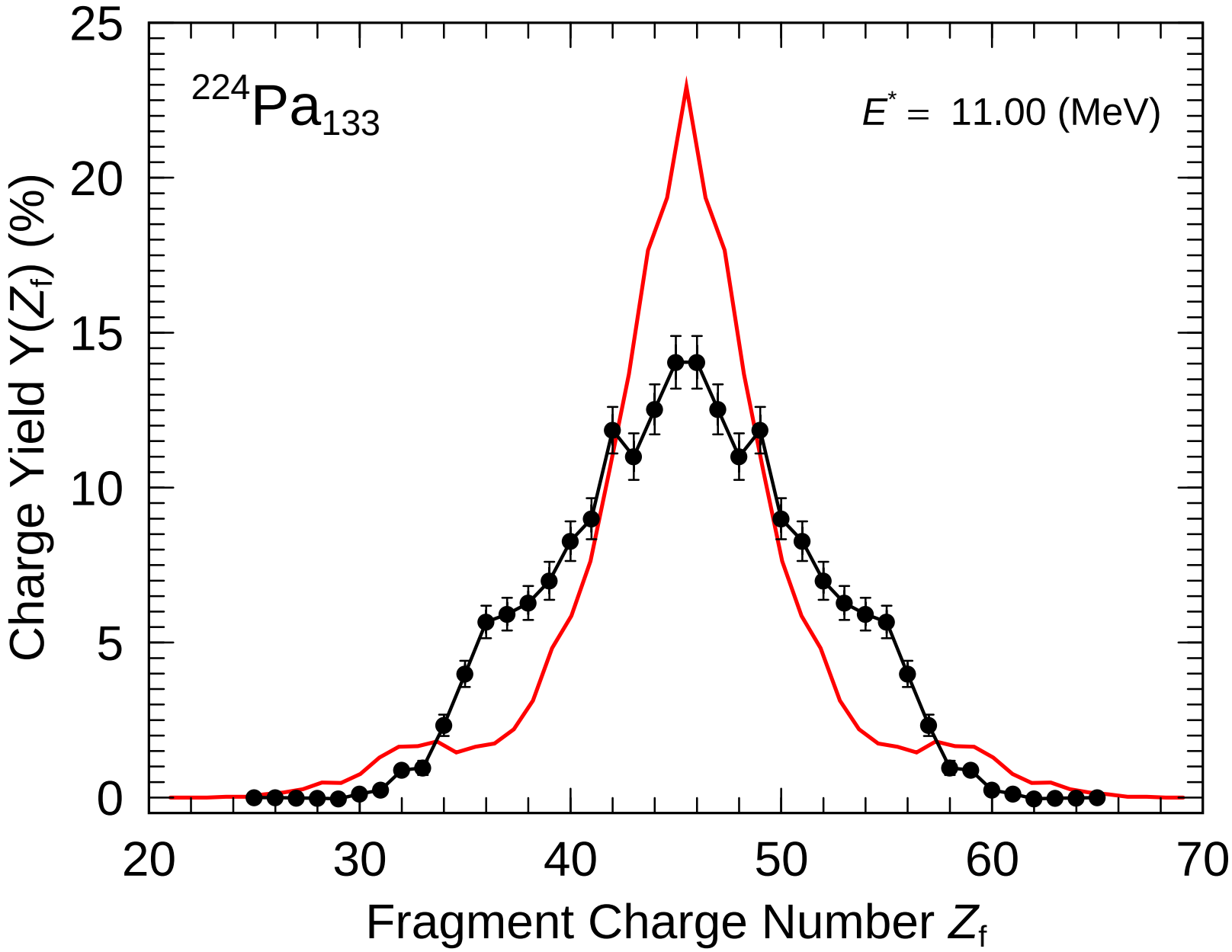
$^{224}Pa_{133}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
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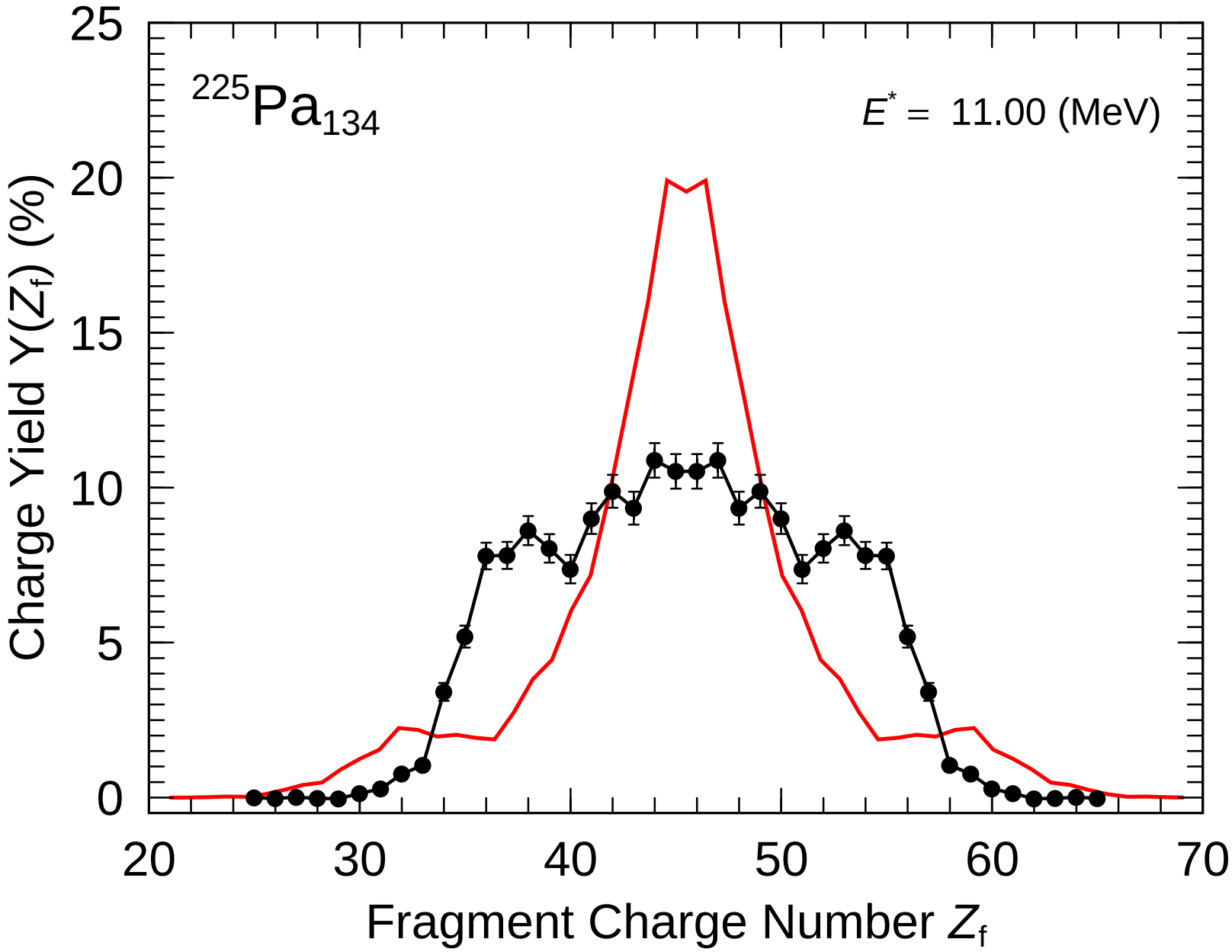
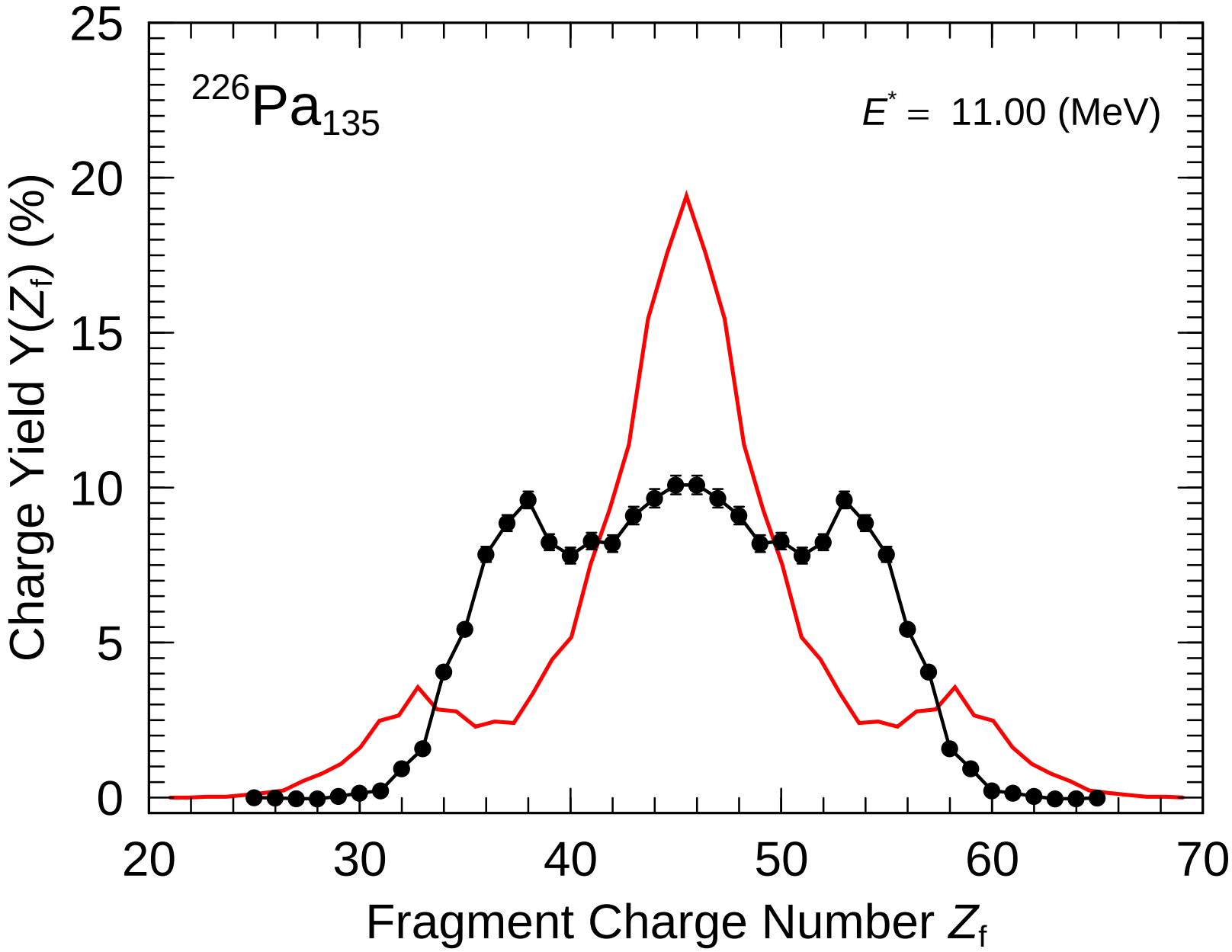
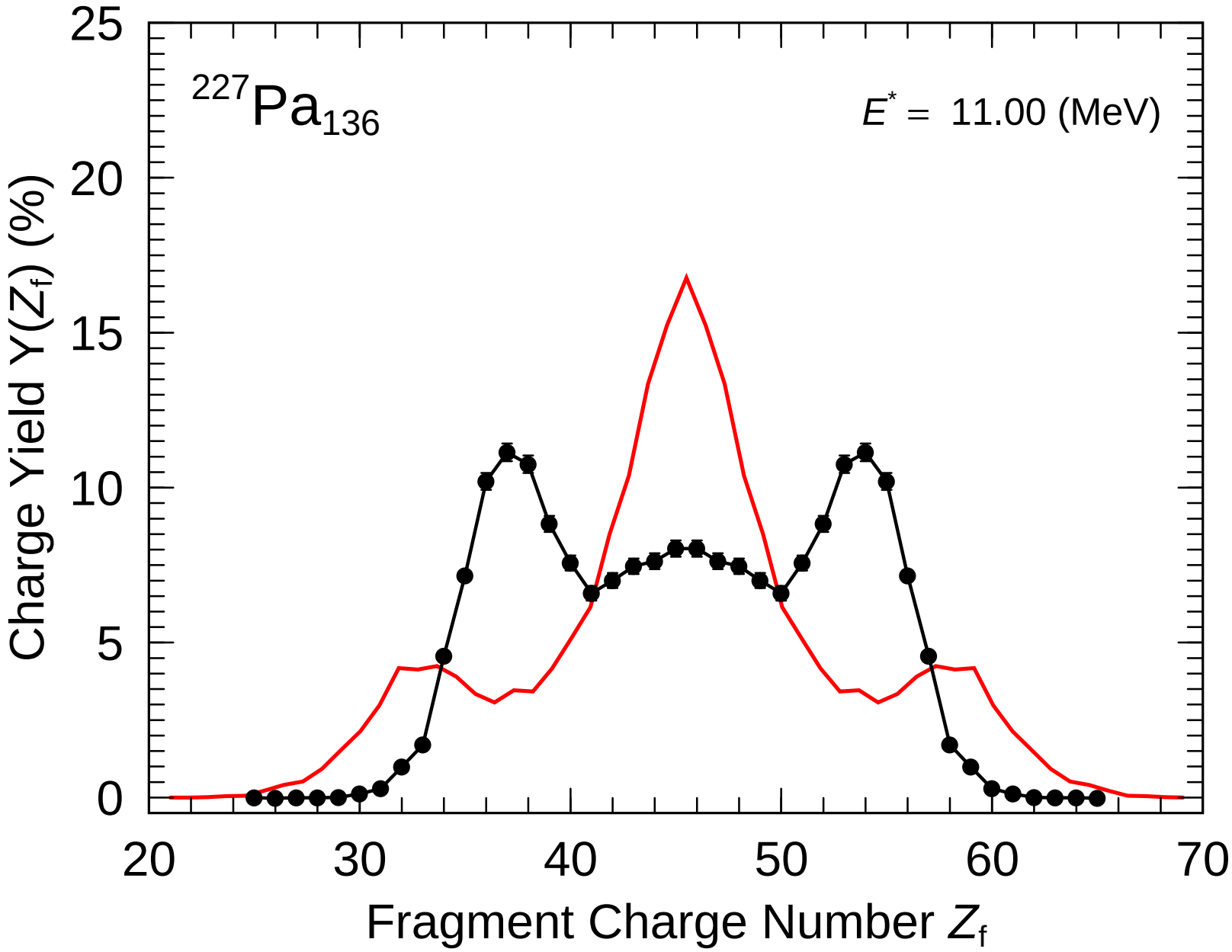
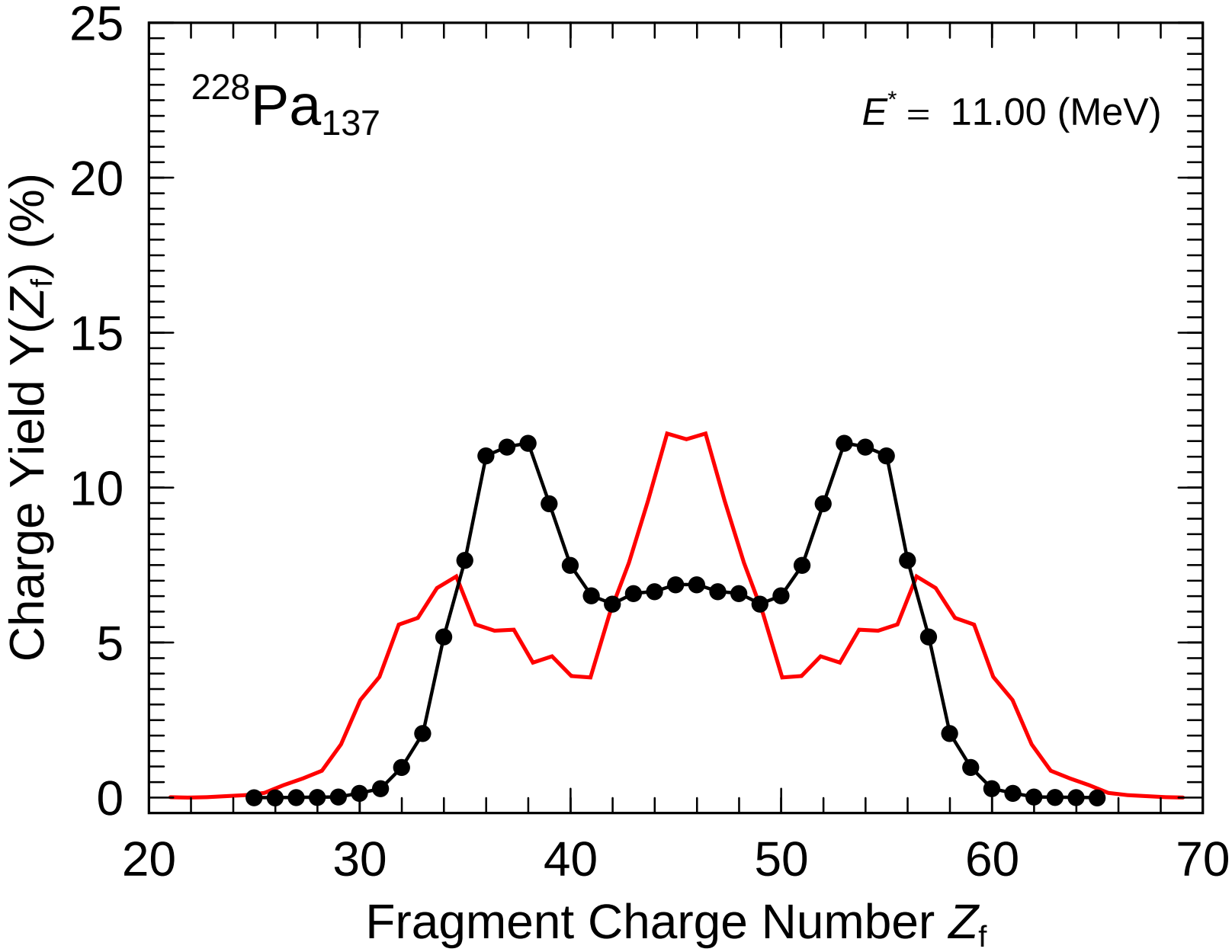
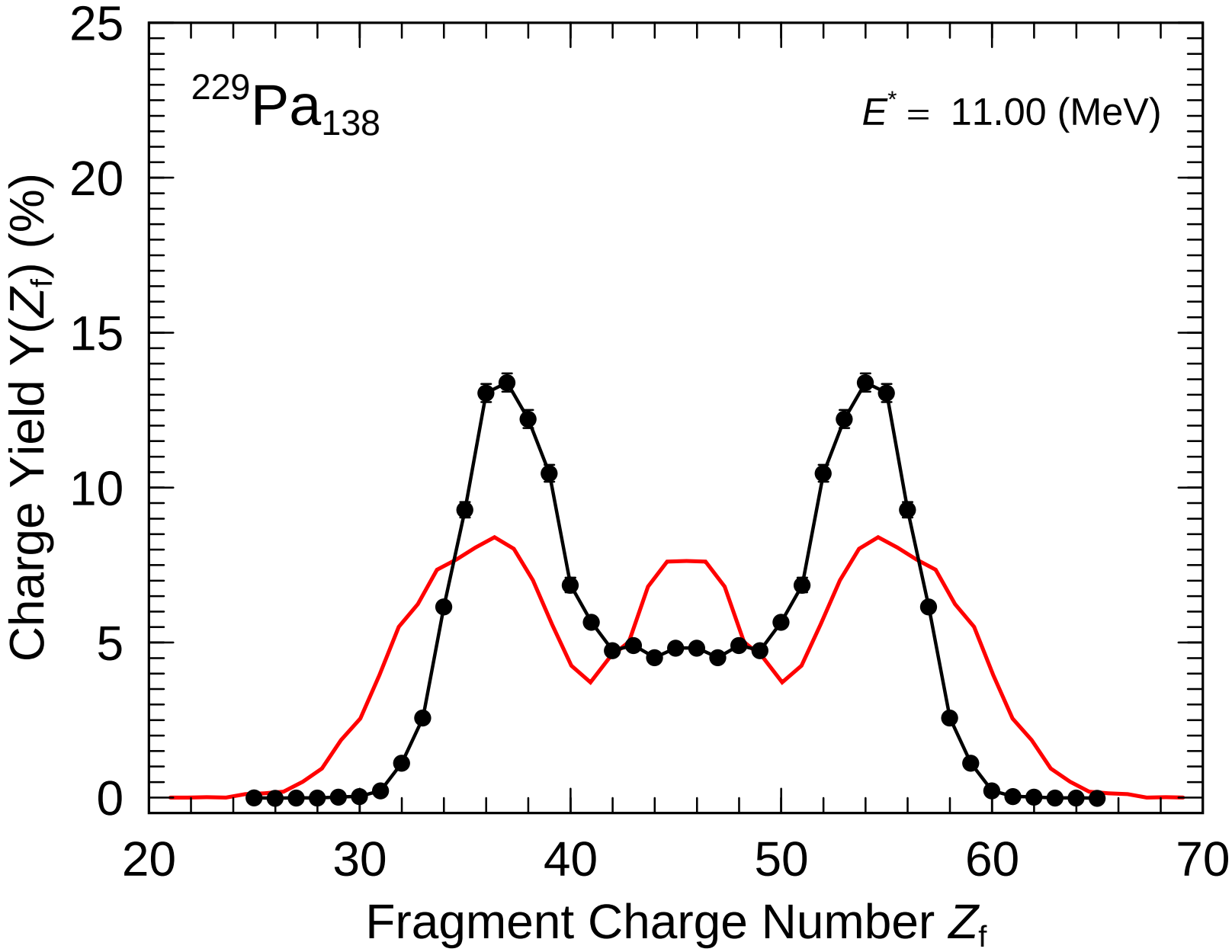
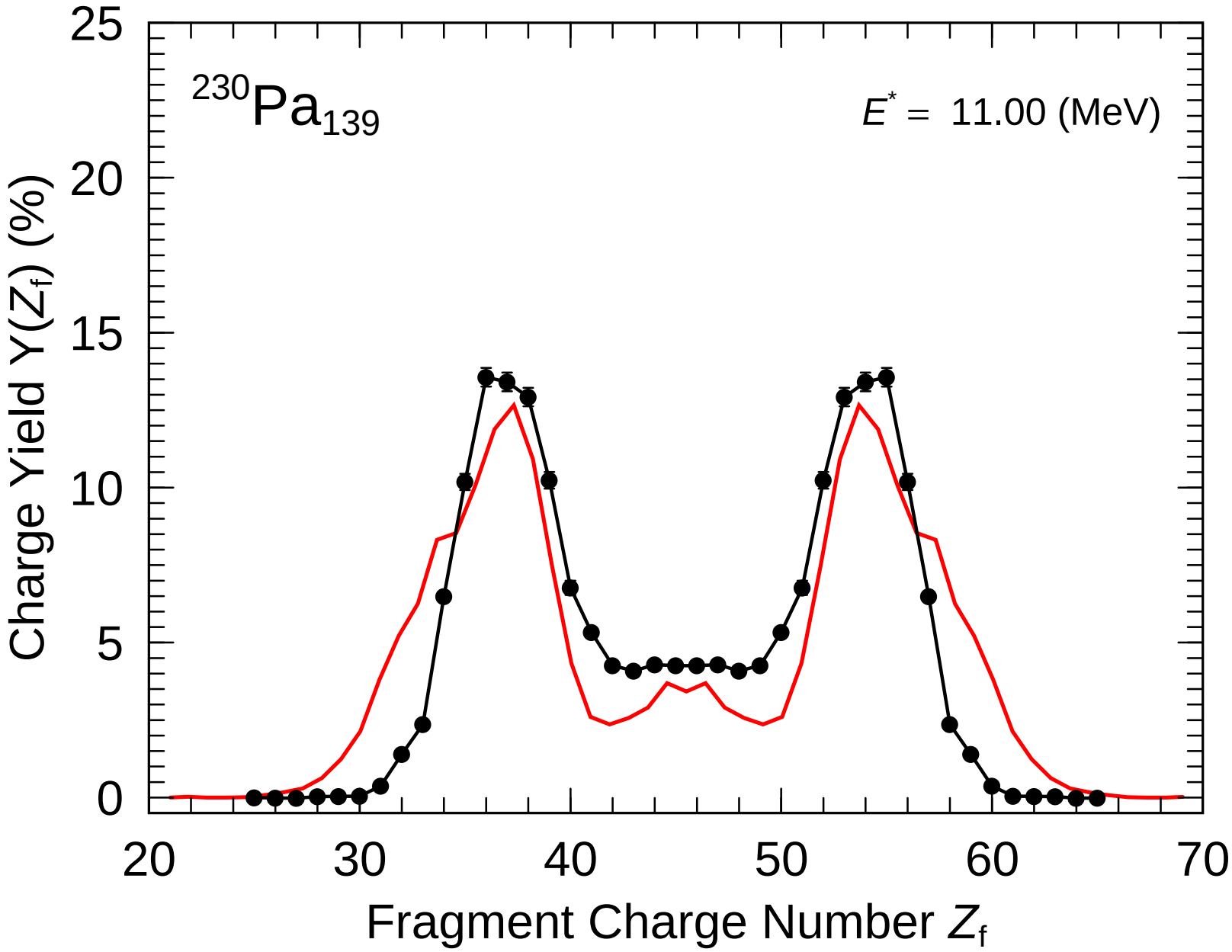

$^{225}Pa_{134}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

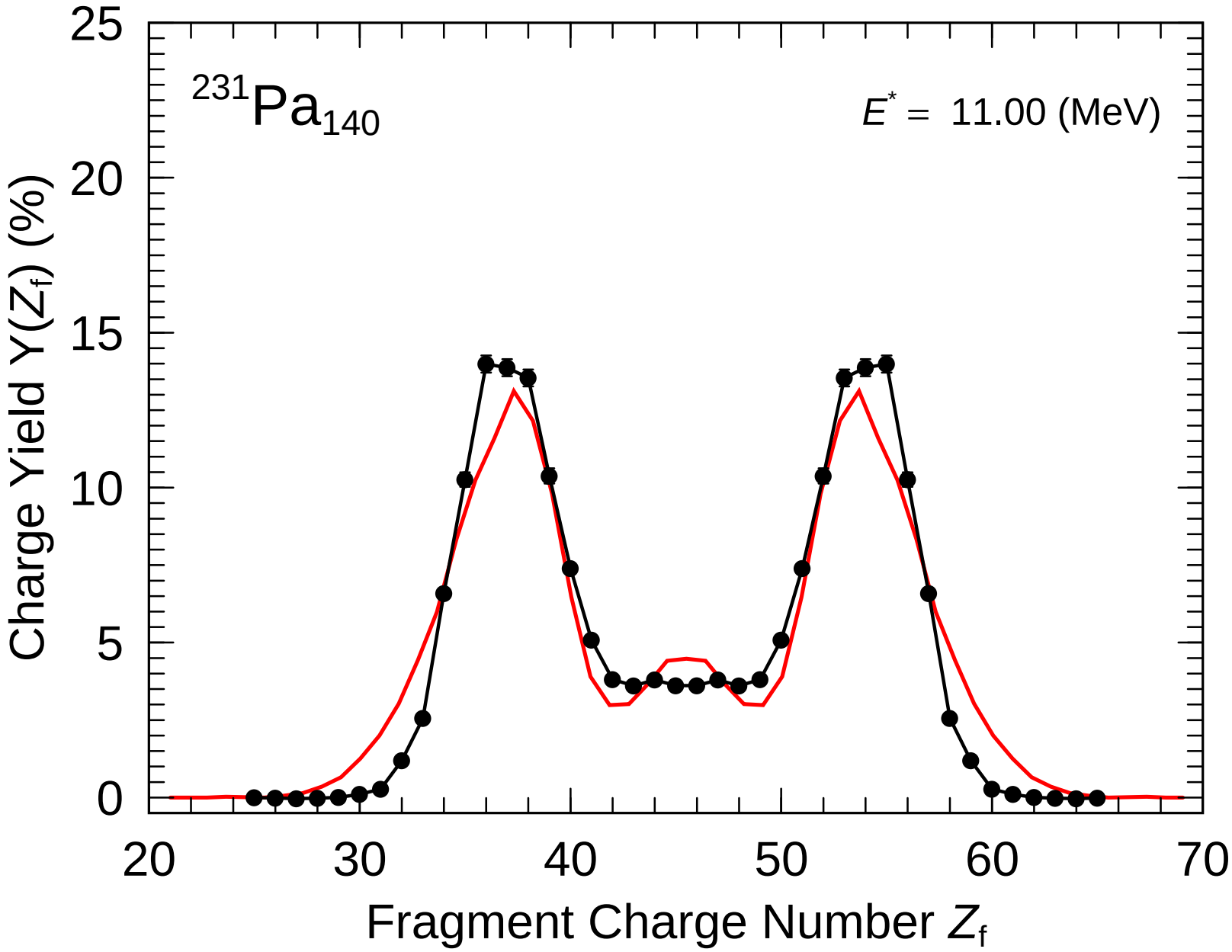

$^{226}Pa_{135}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

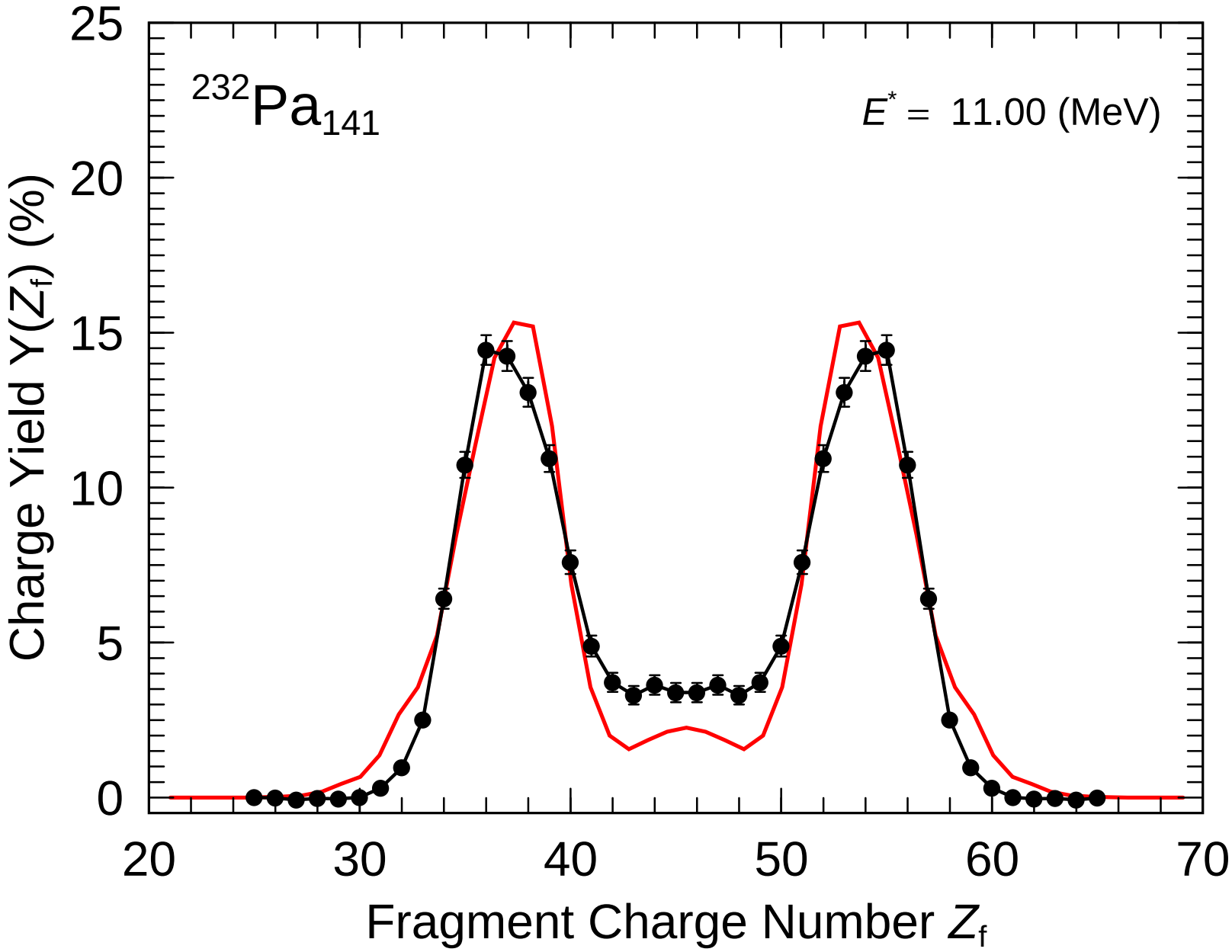

$^{227}Pa_{136}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

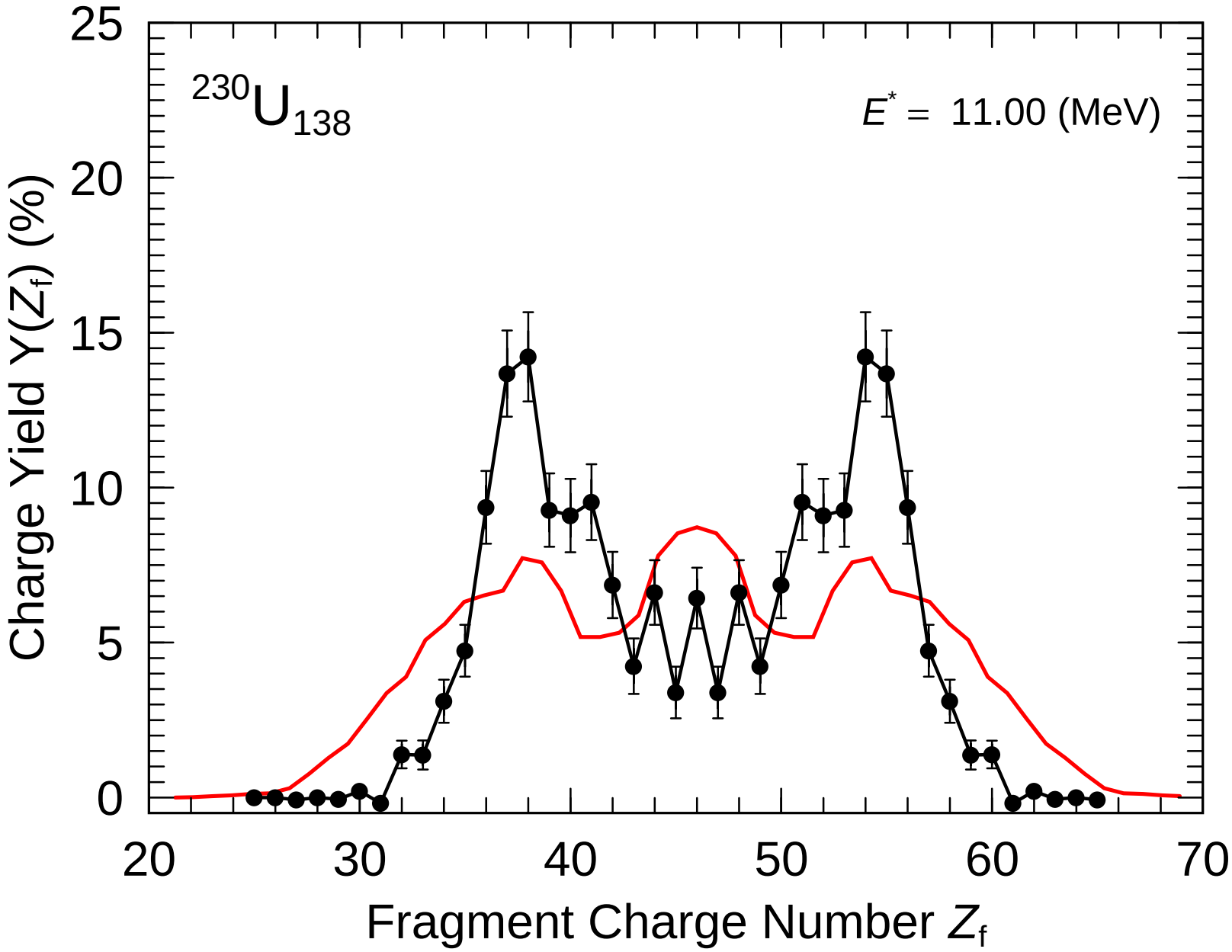

$^{228}Pa_{137}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

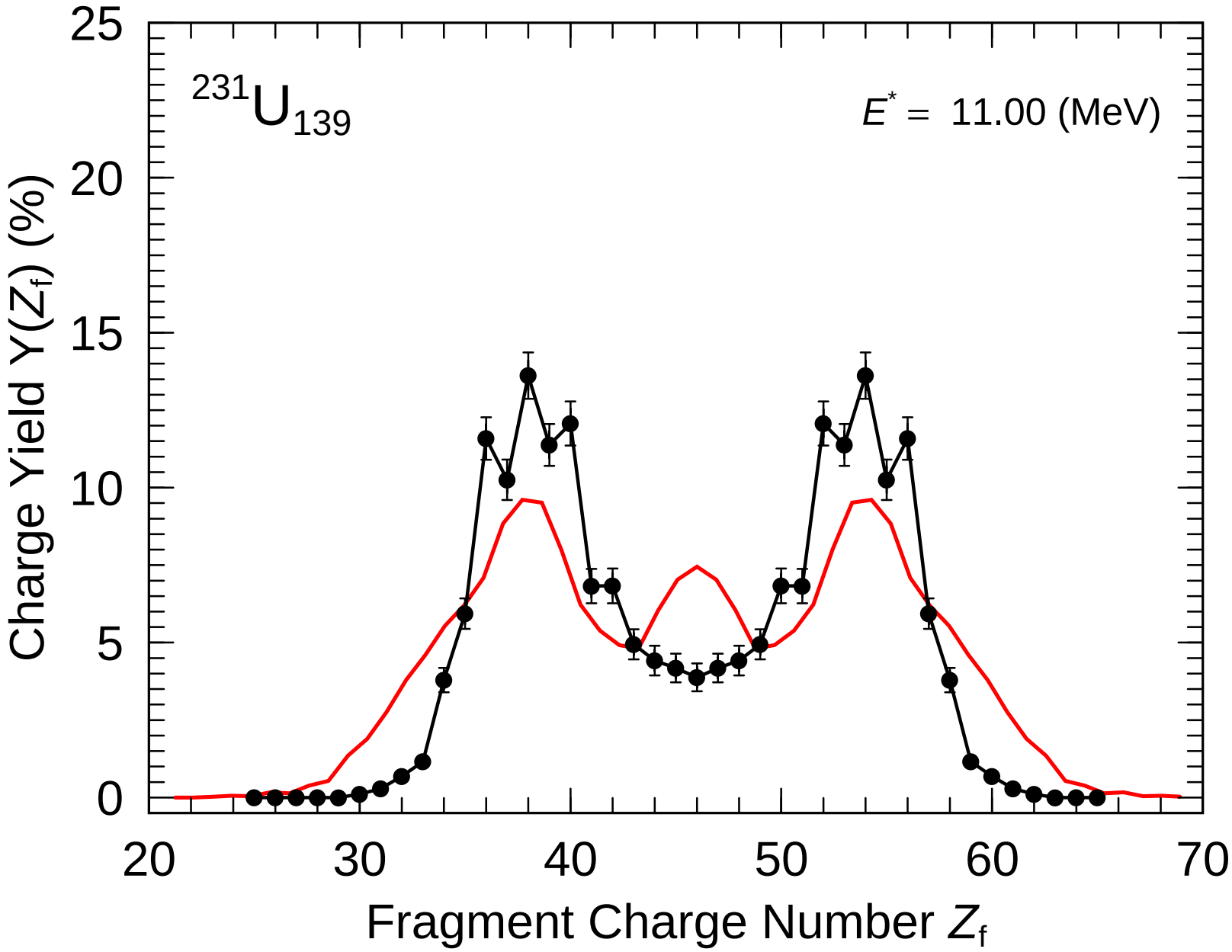

$^{229}Pa_{138}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

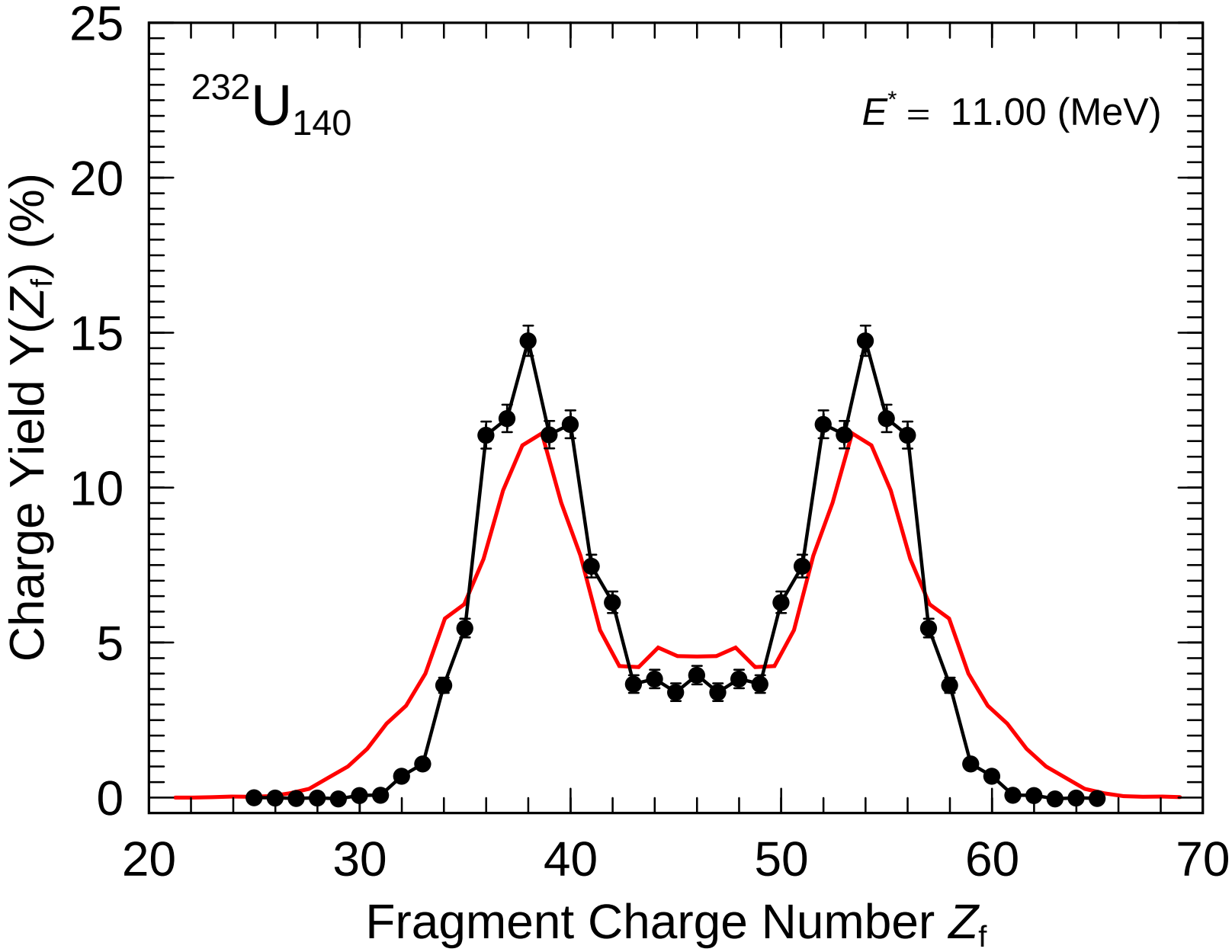

$^{230}Pa_{139}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

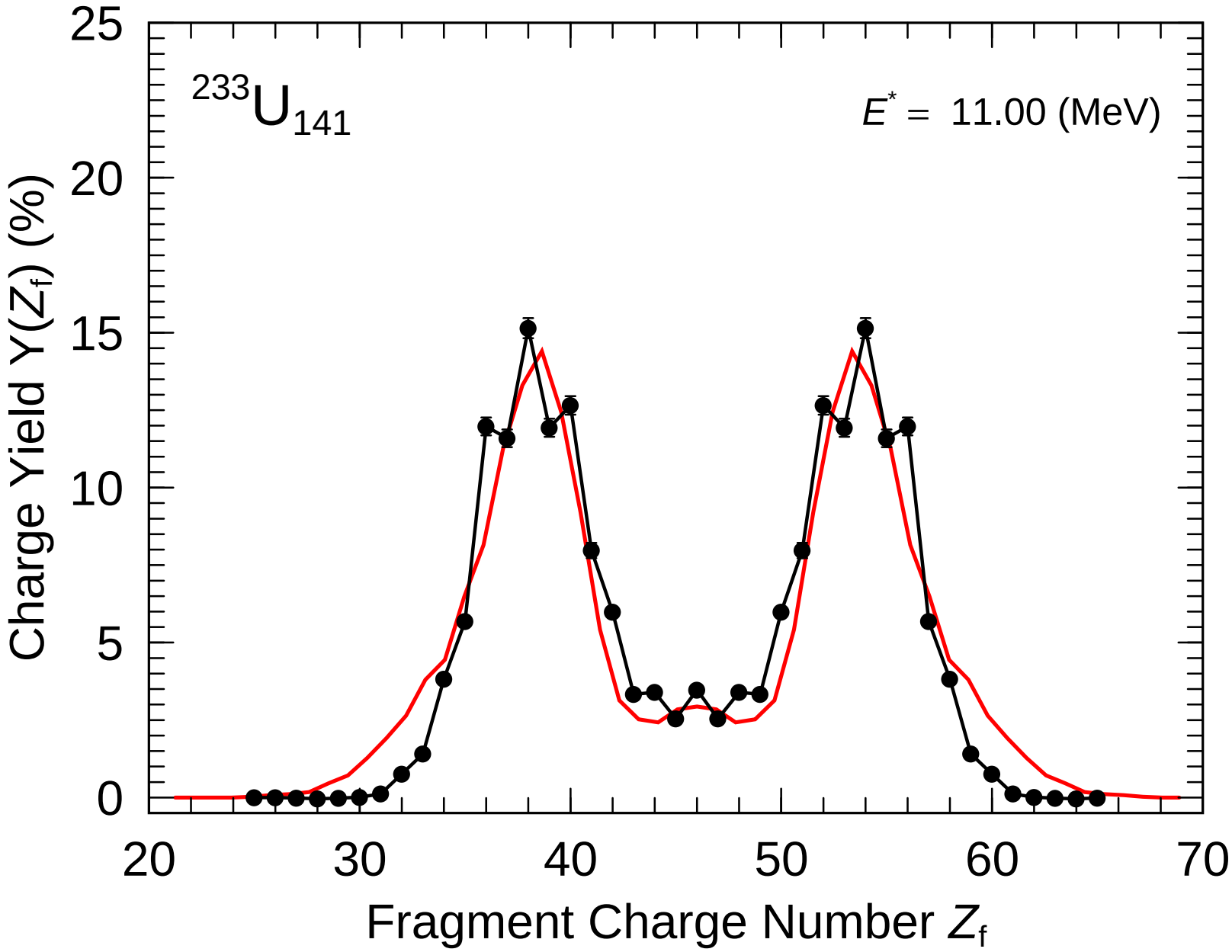

$^{231}Pa_{140}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

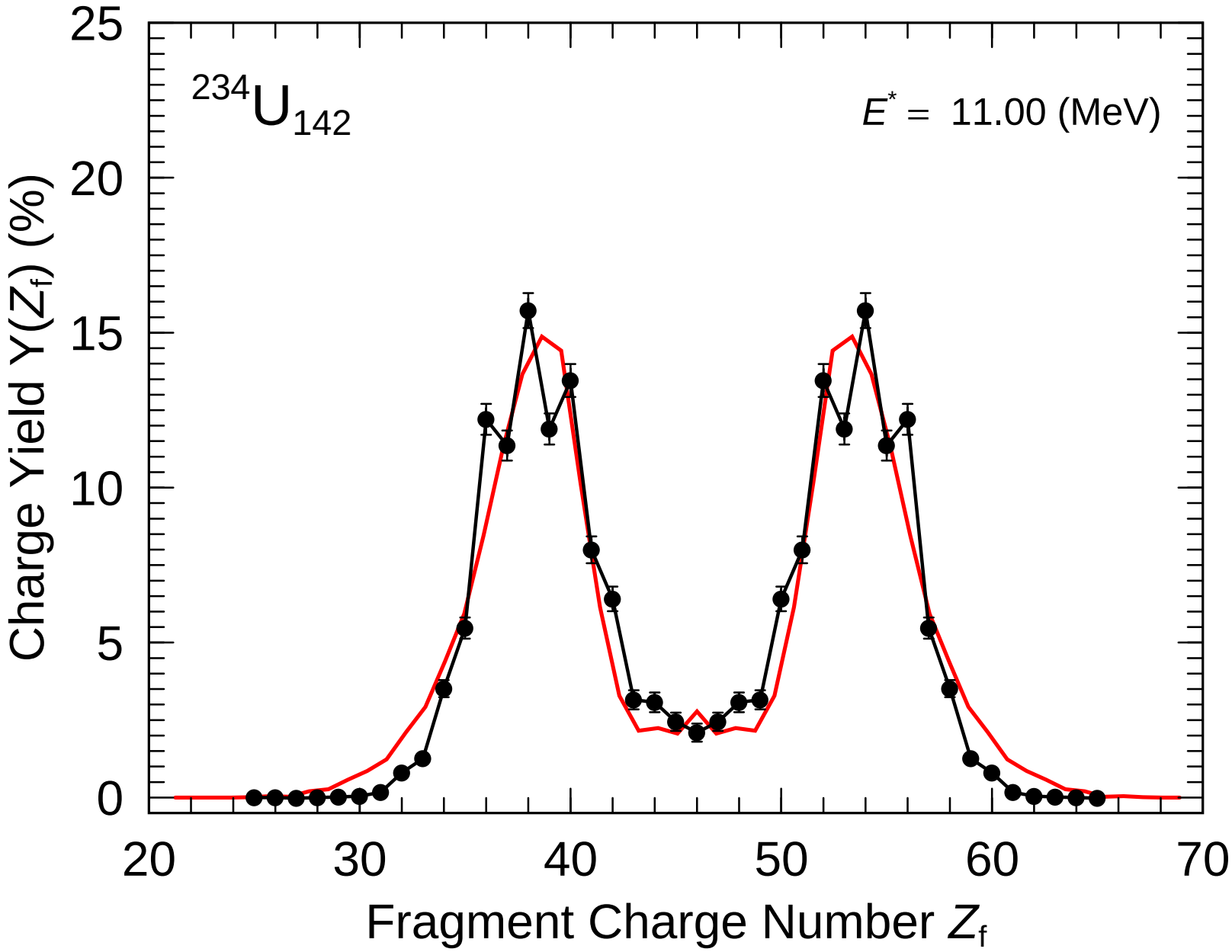

$^{232}Pa_{141}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

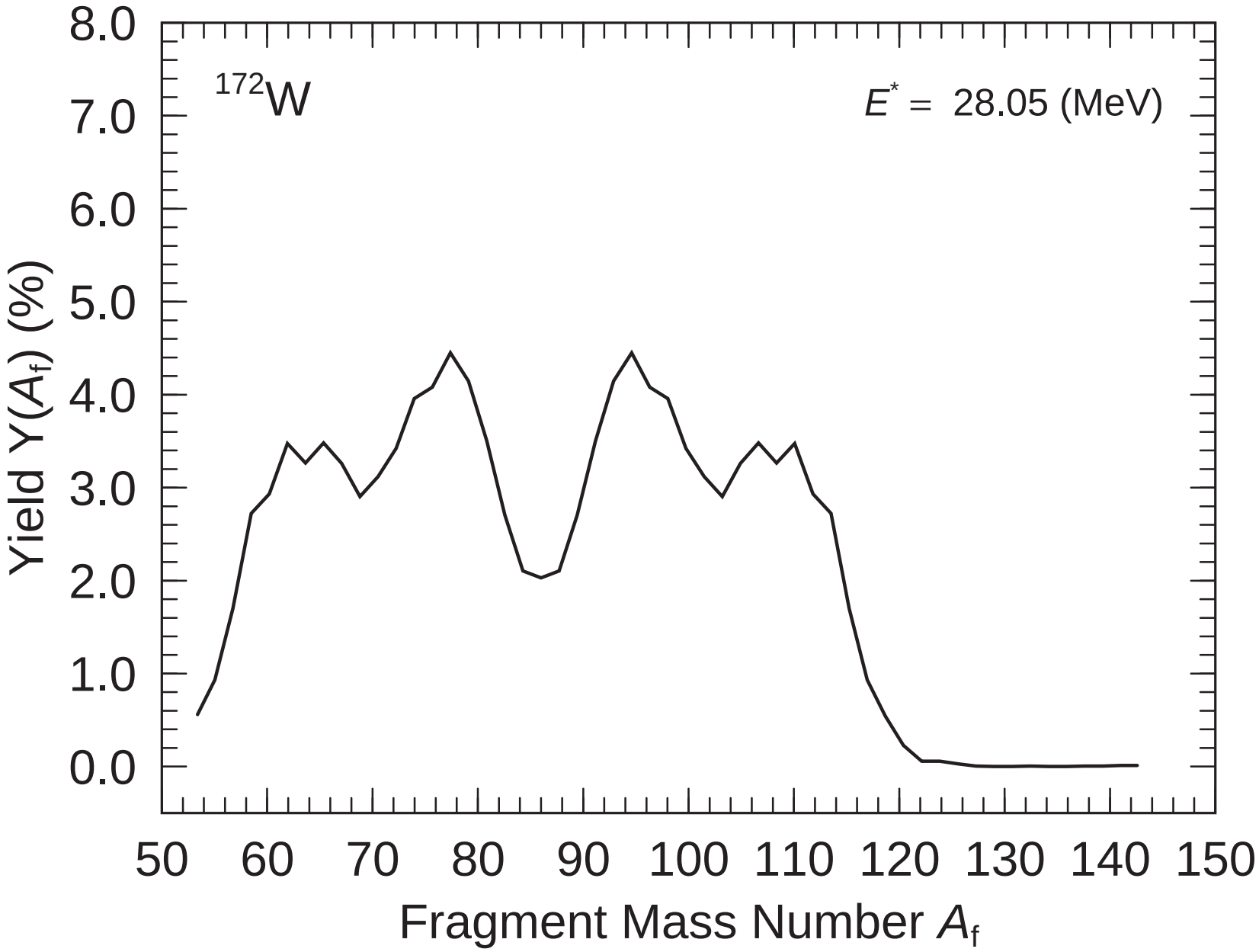

$^{230}U_{138}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

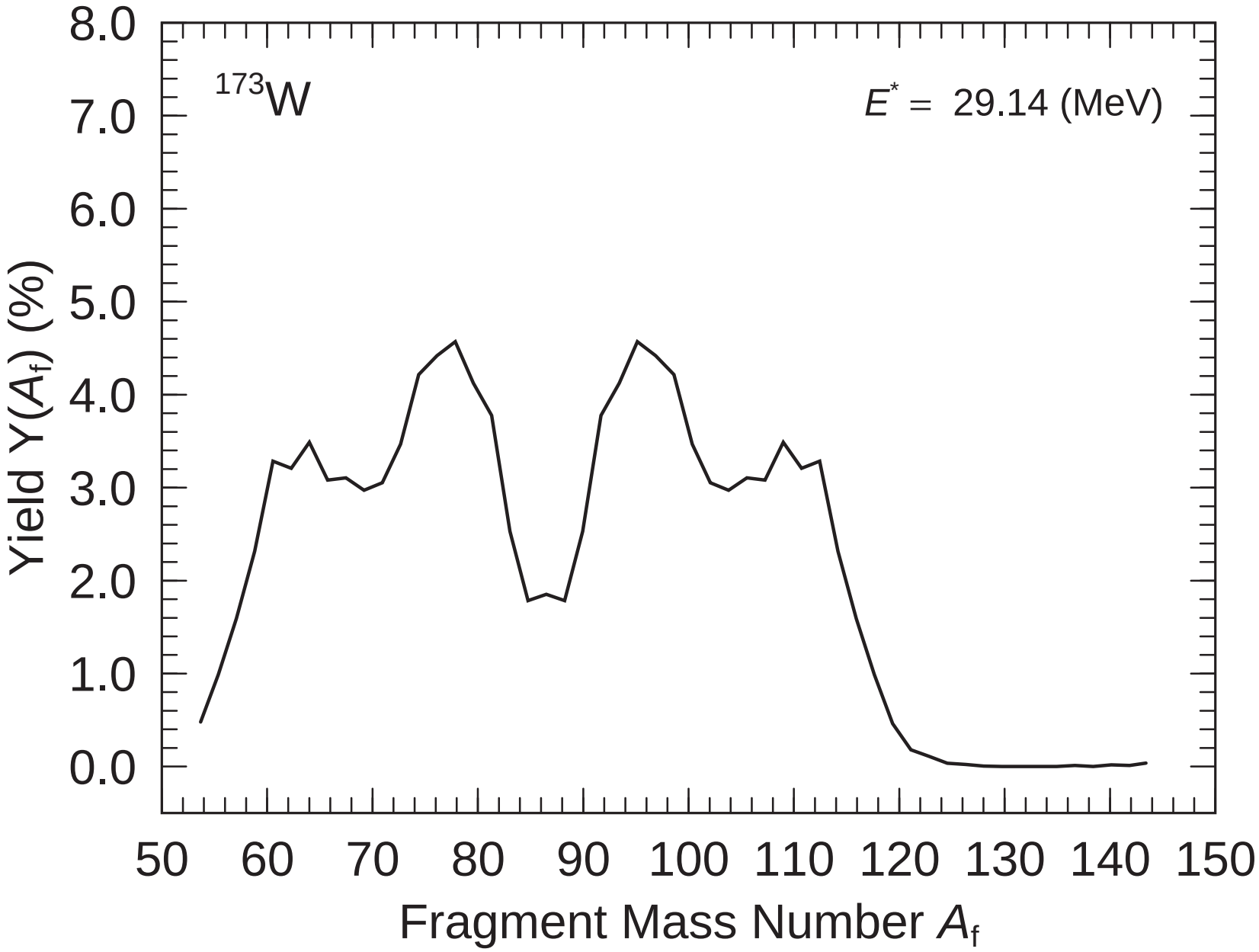

$^{231}U_{139}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

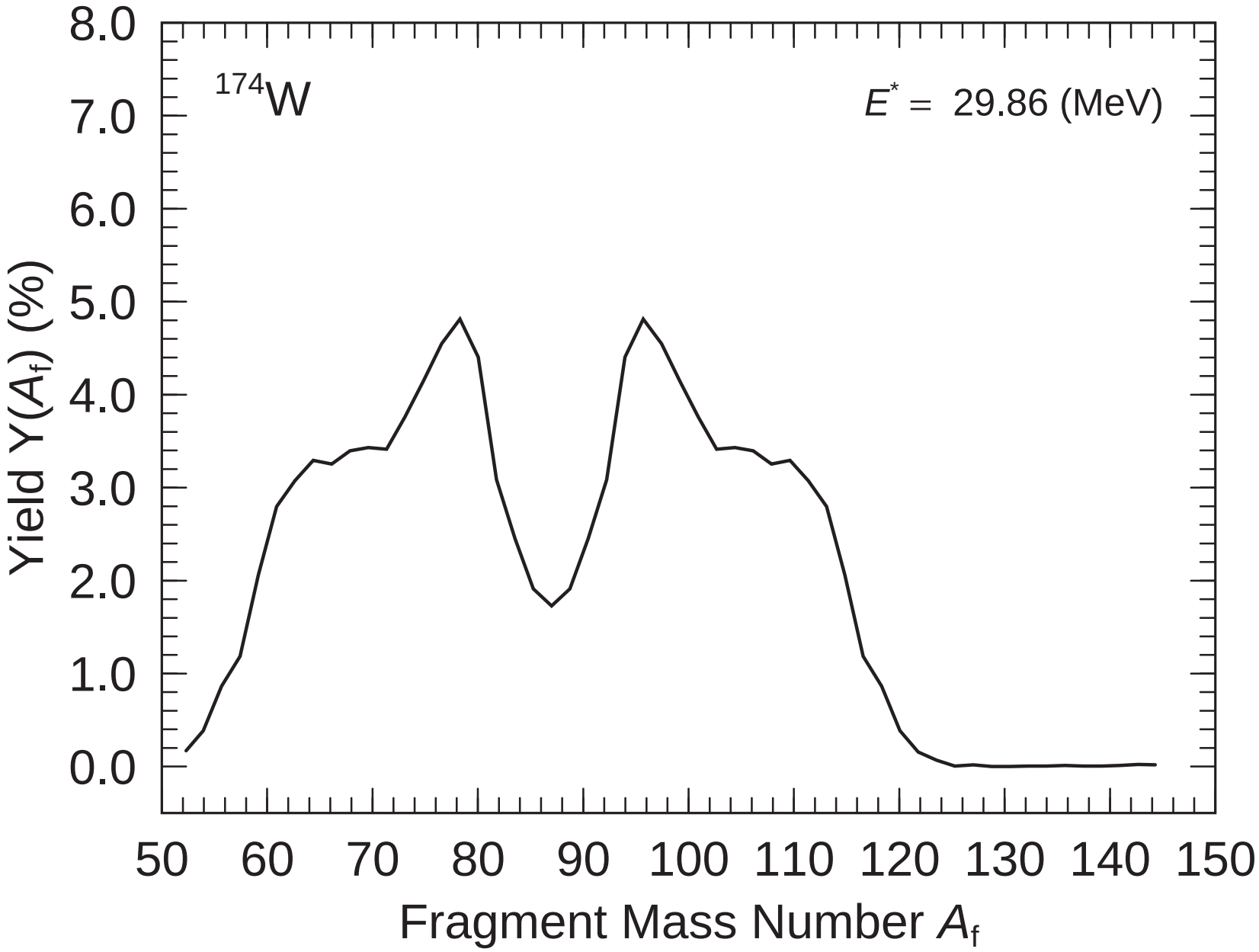

$^{232}U_{140}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

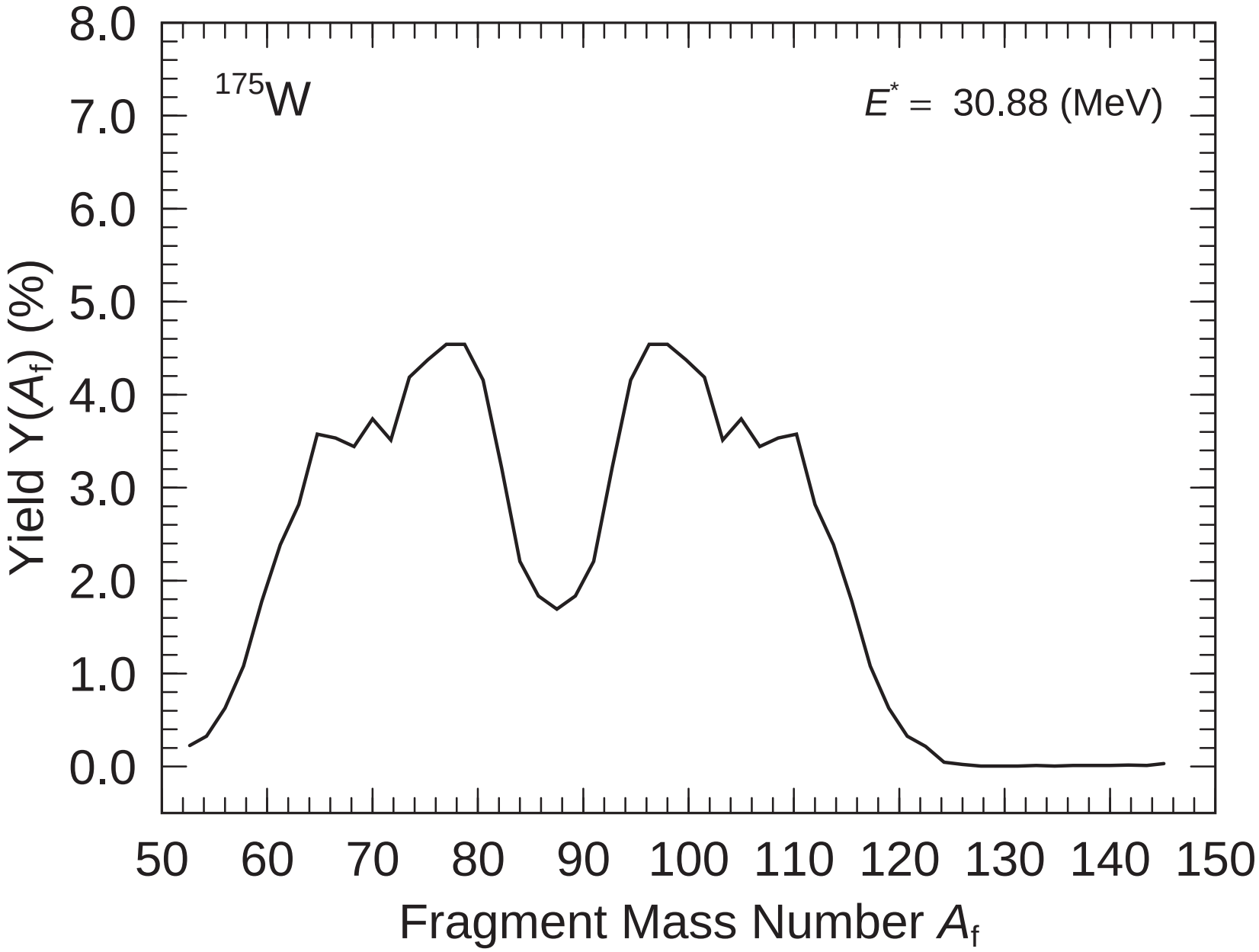

$^{233}U_{141}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

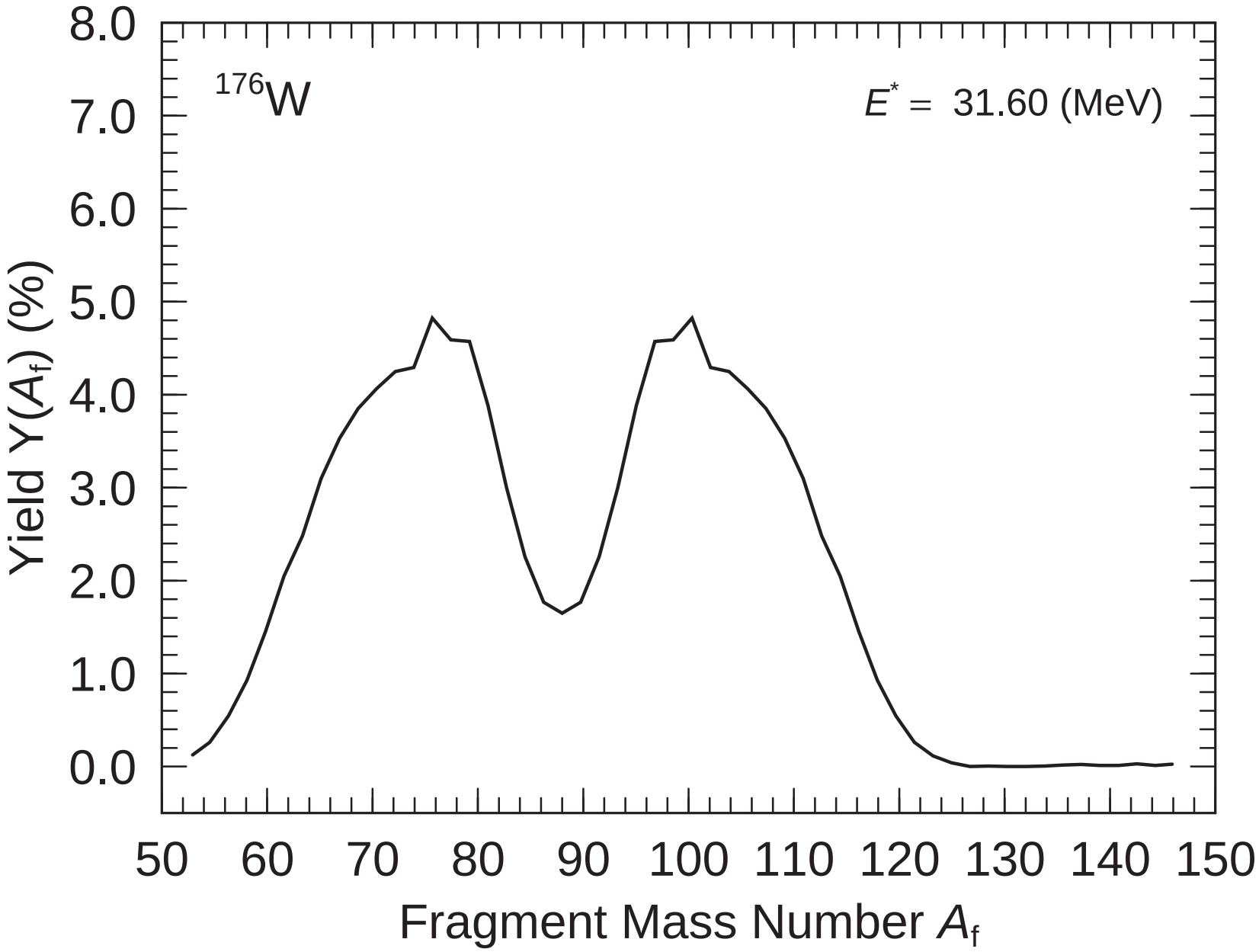

$^{234}U_{142}$
E^* = 11.00 (MeV)
Charge Yield Y(Z_f) (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
20
30
40
50
60
70

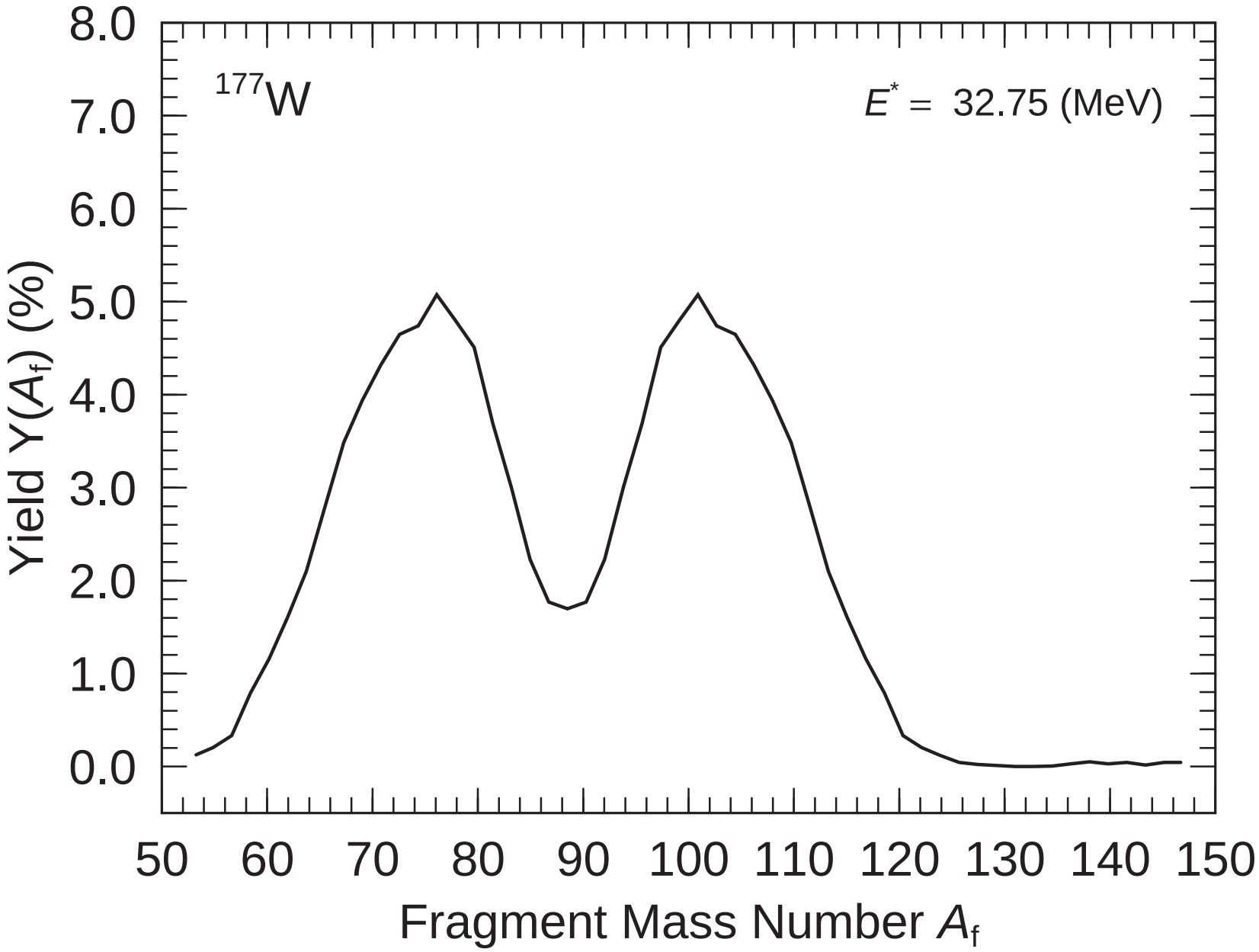

^{172}W
E^* = 28.05 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

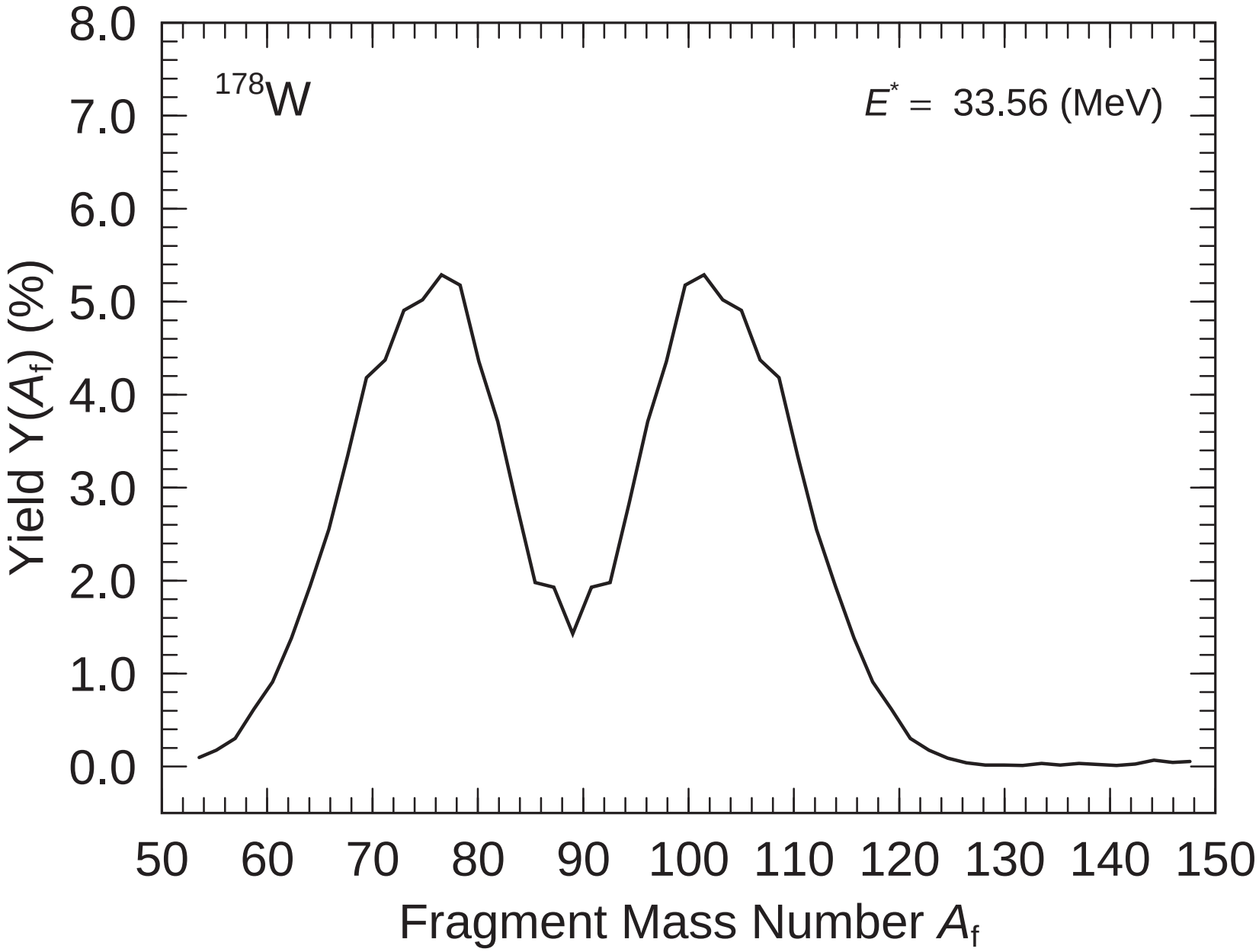

^{173}W
E^* = 29.14 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

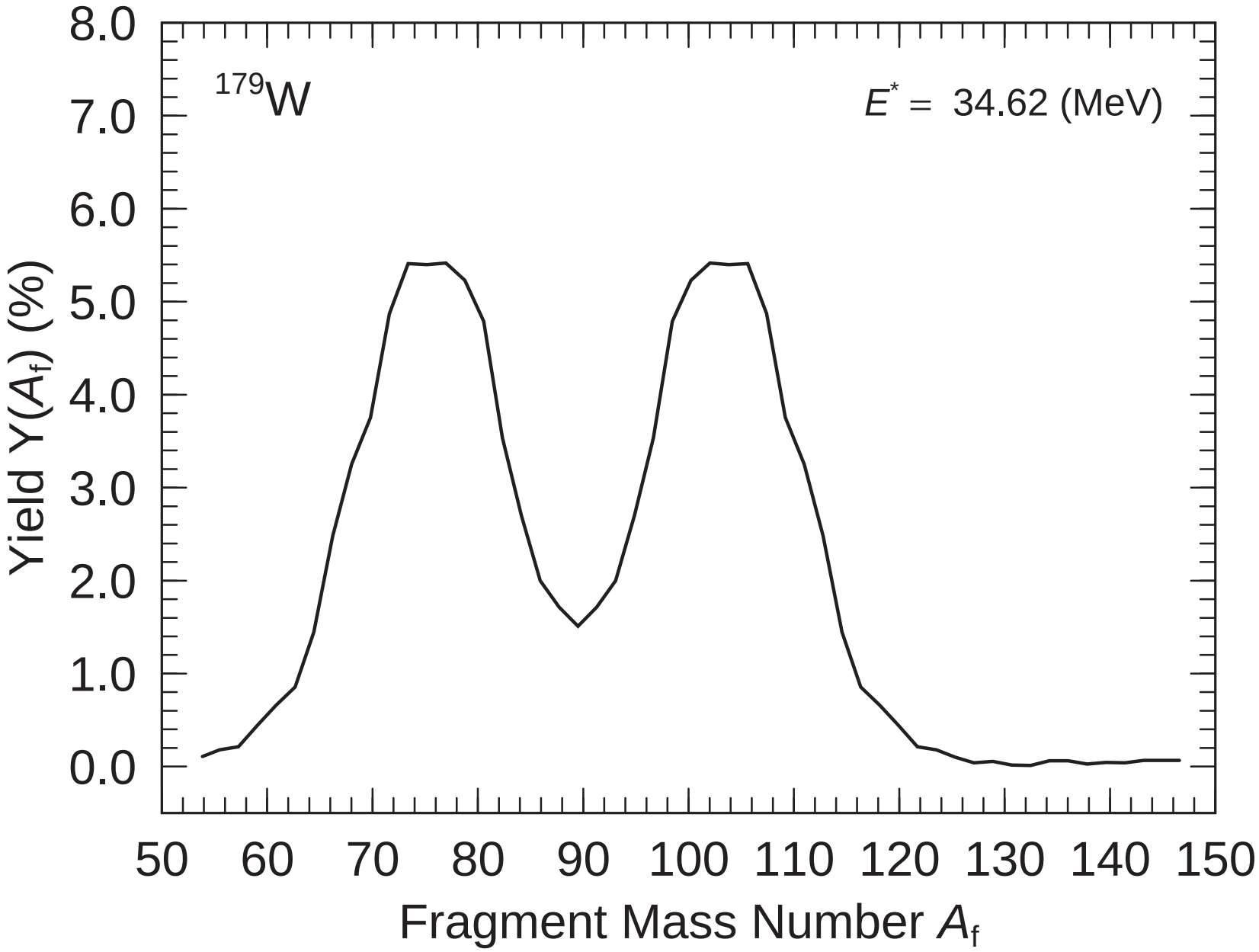

^{174}W
E^* = 29.86 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

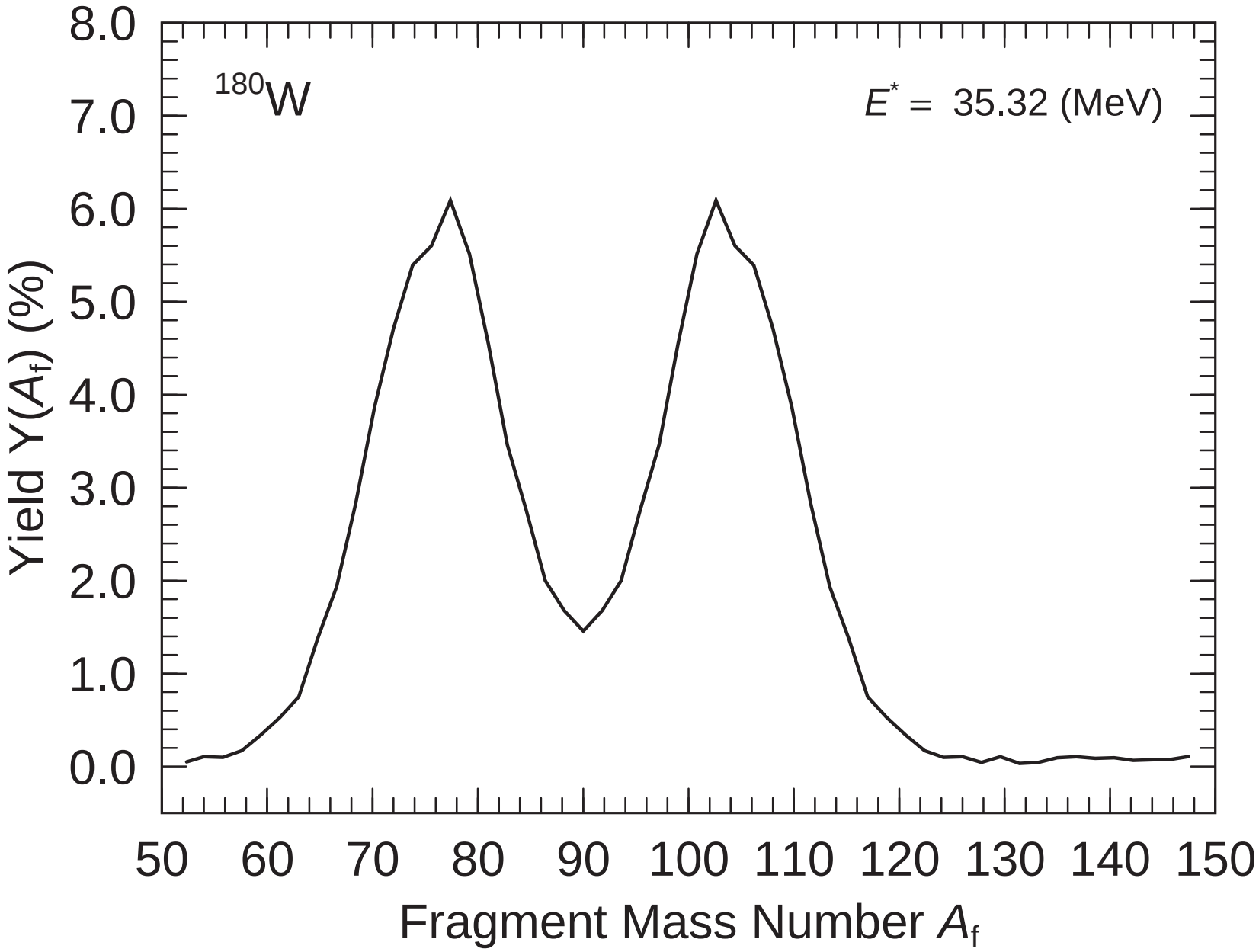

^{175}W
E^* = 30.88 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

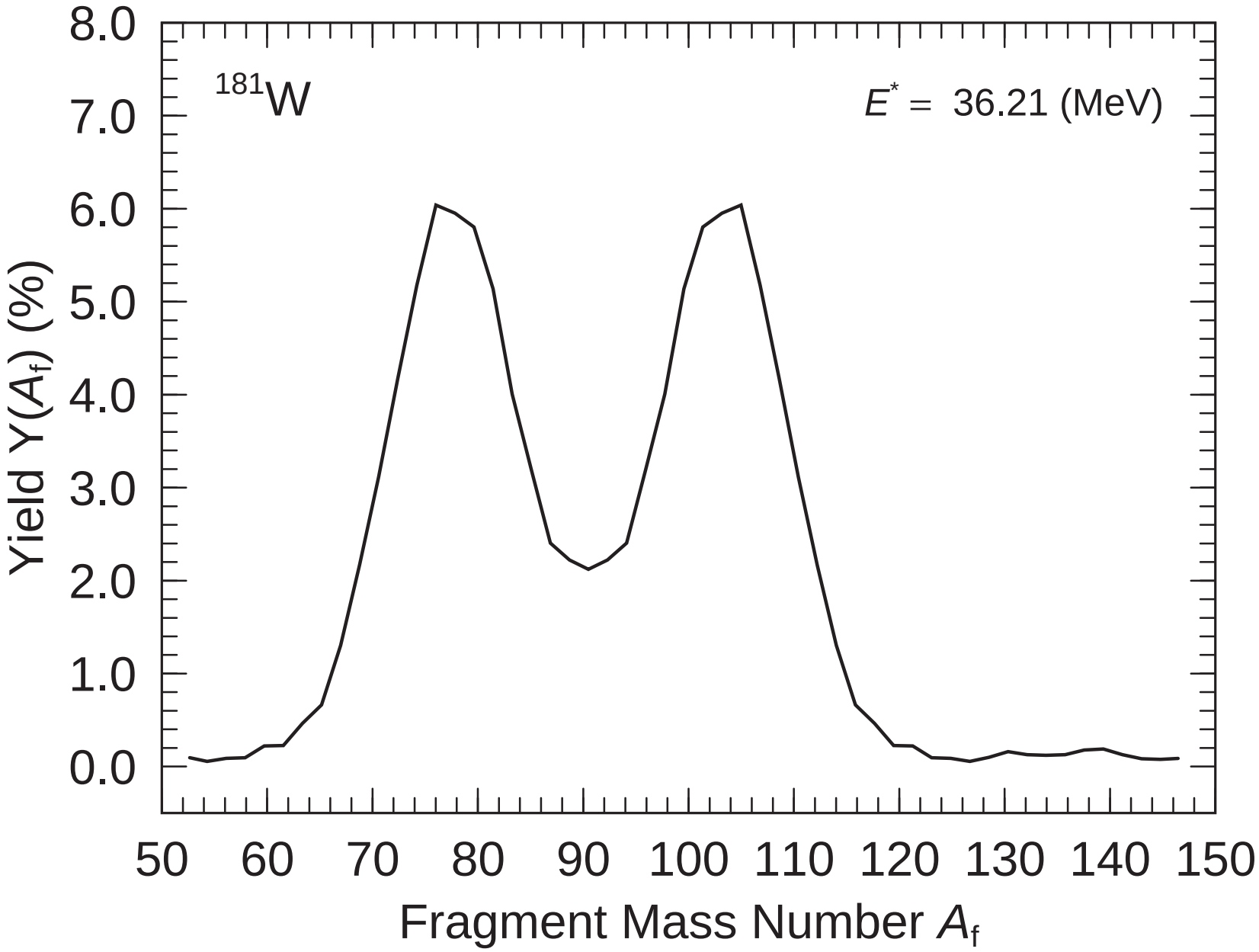

^{176}W
E^* = 31.60 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

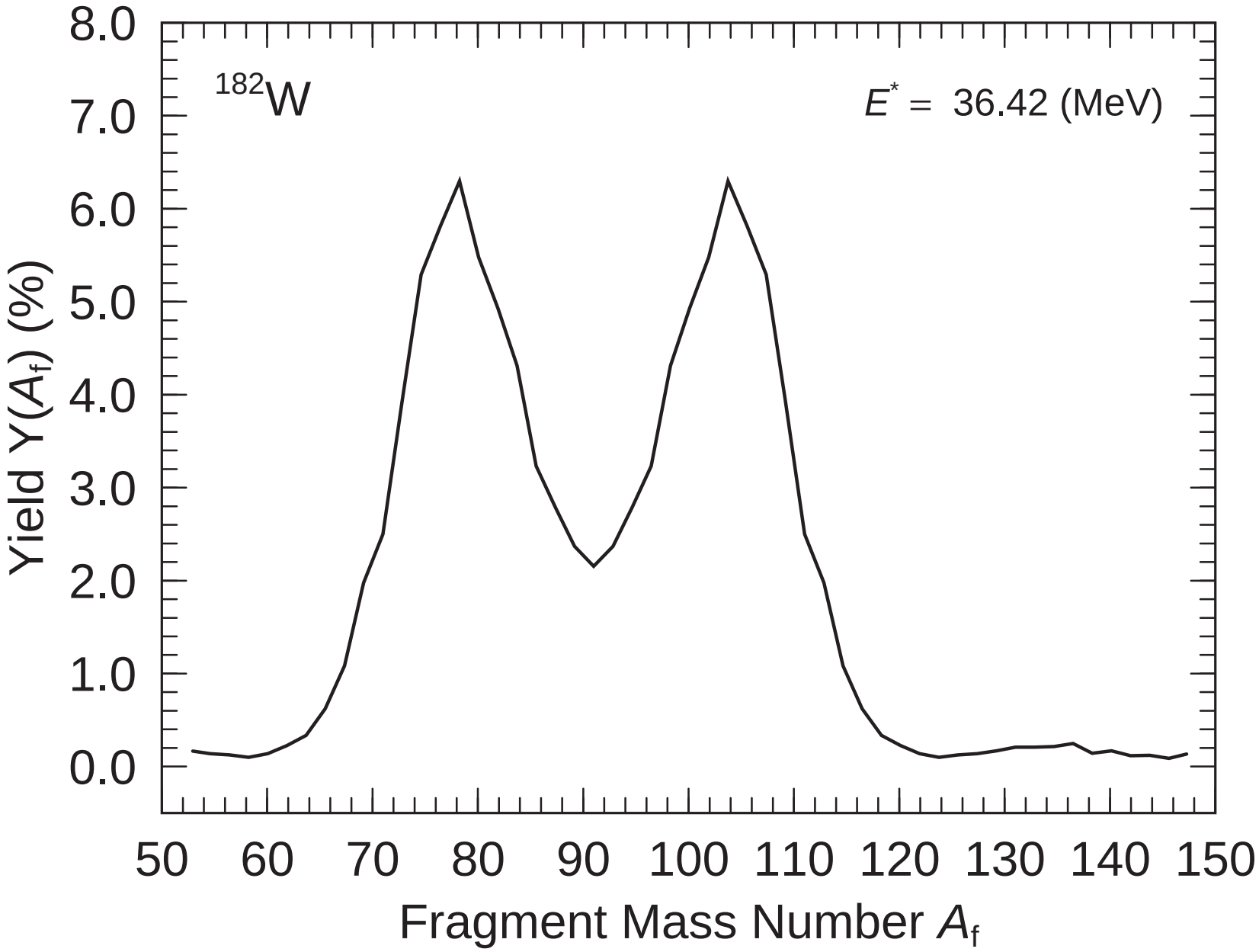

^{177}W
E^* = 32.75 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

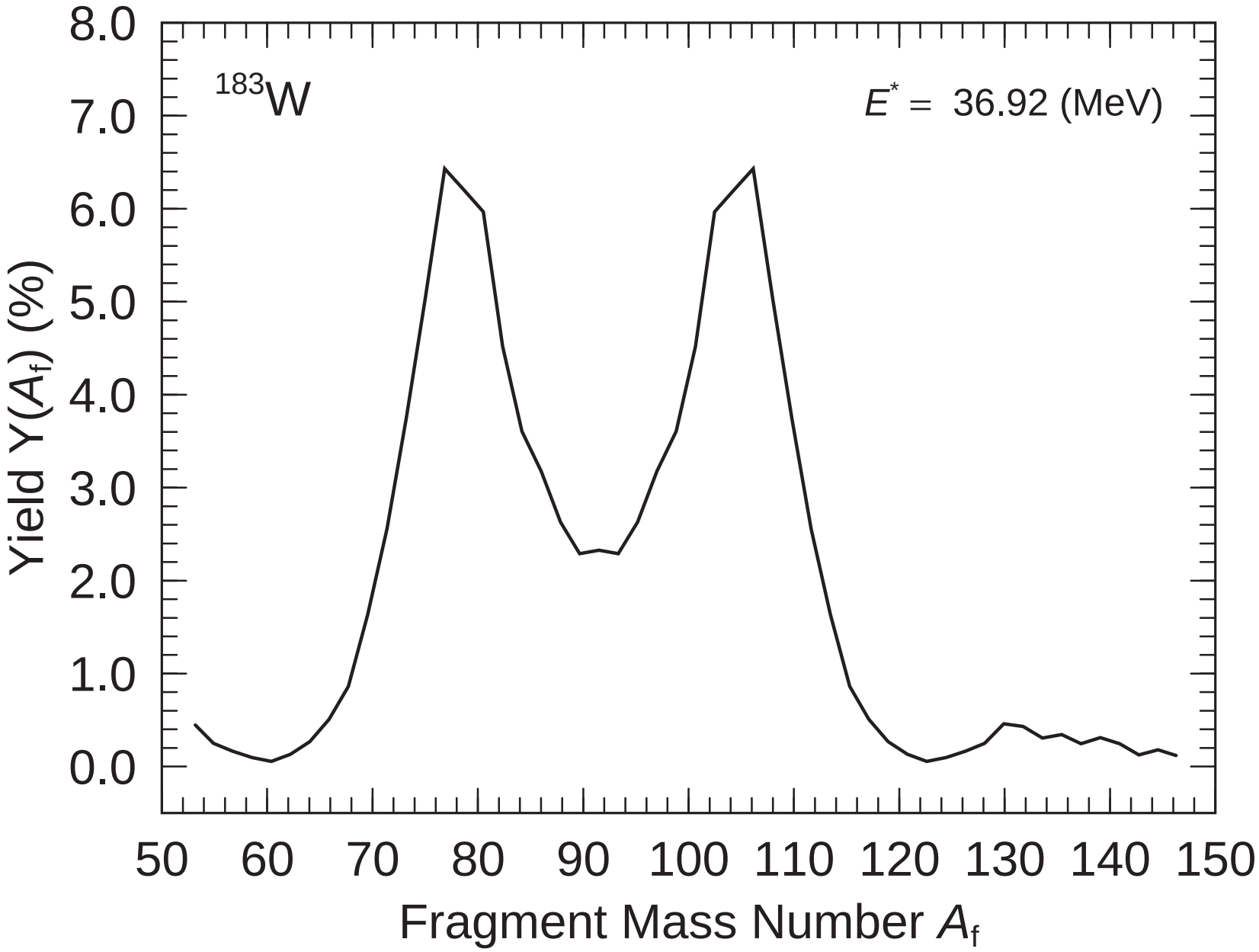

^{178}W
E^* = 33.56 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

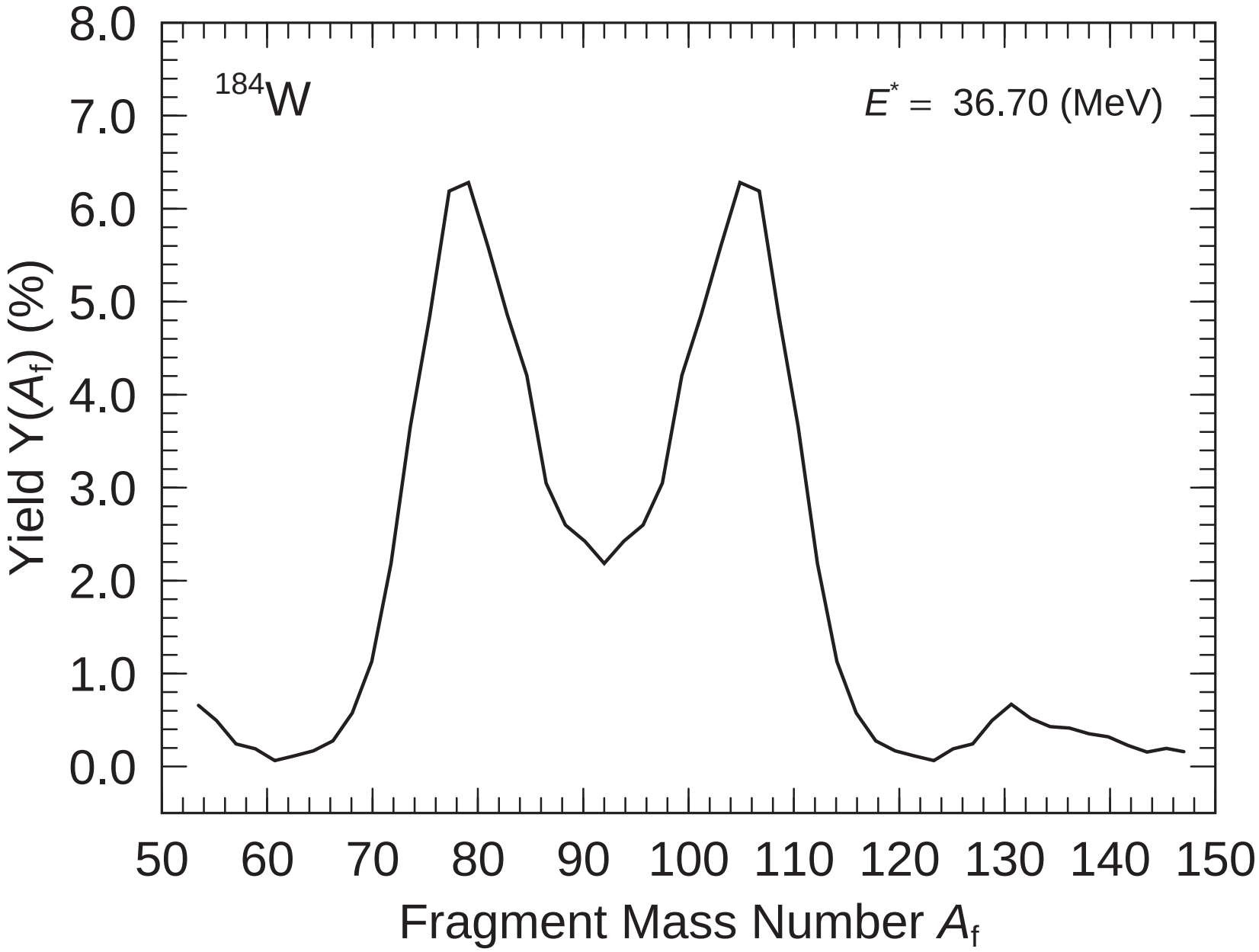

^{179}W
E^* = 34.62 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

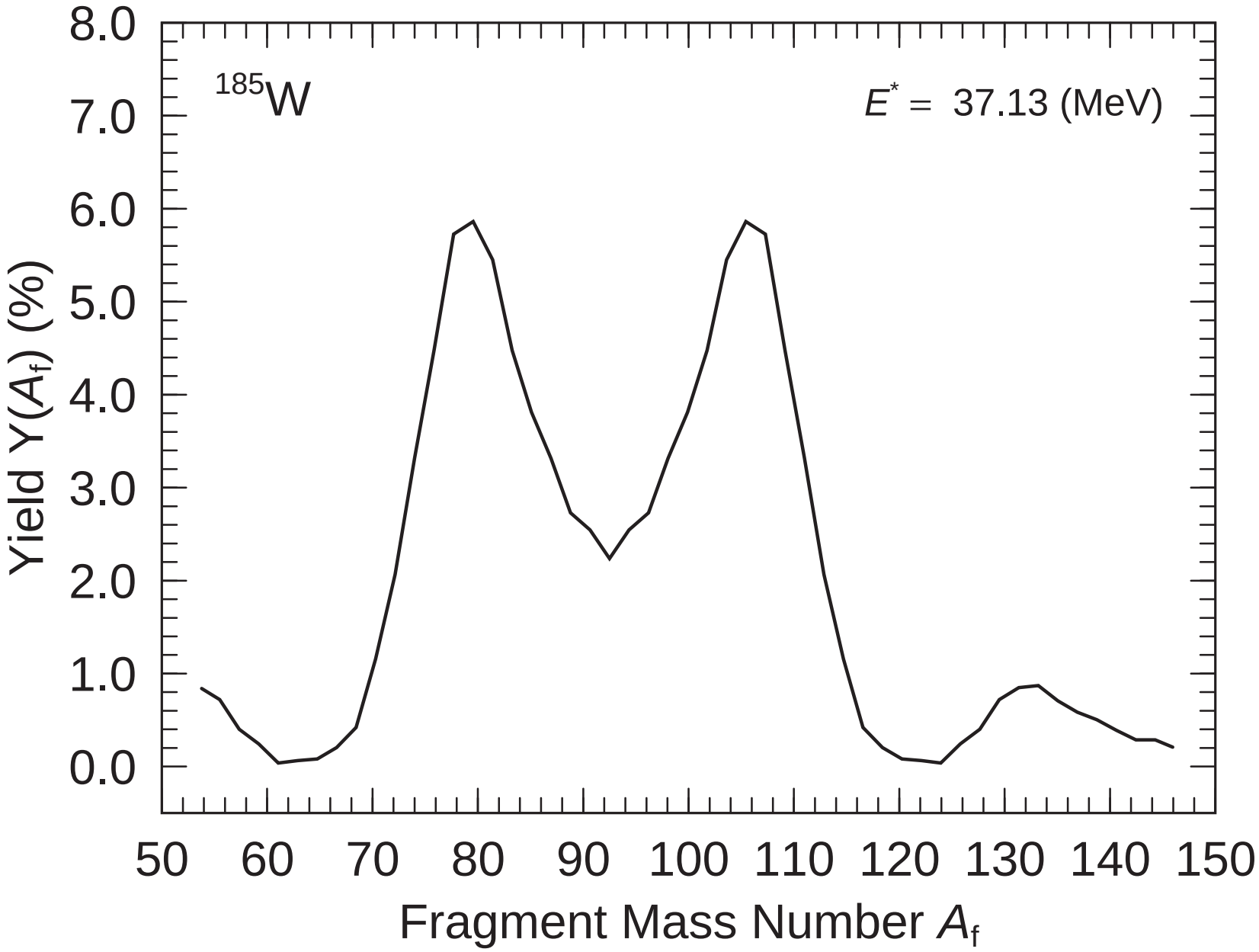

^{180}W
E^* = 35.32 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

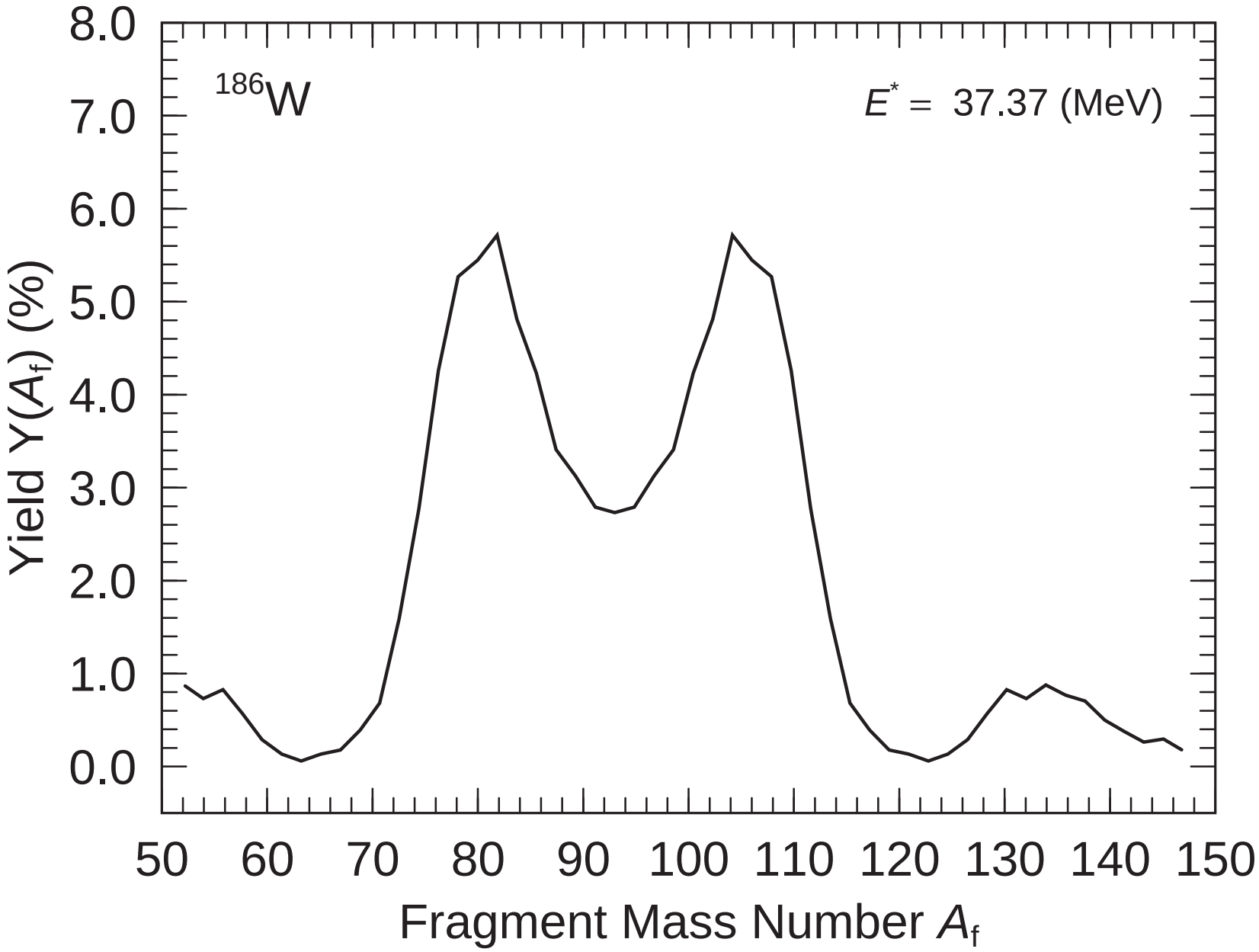

^{181}W
E^* = 36.21 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

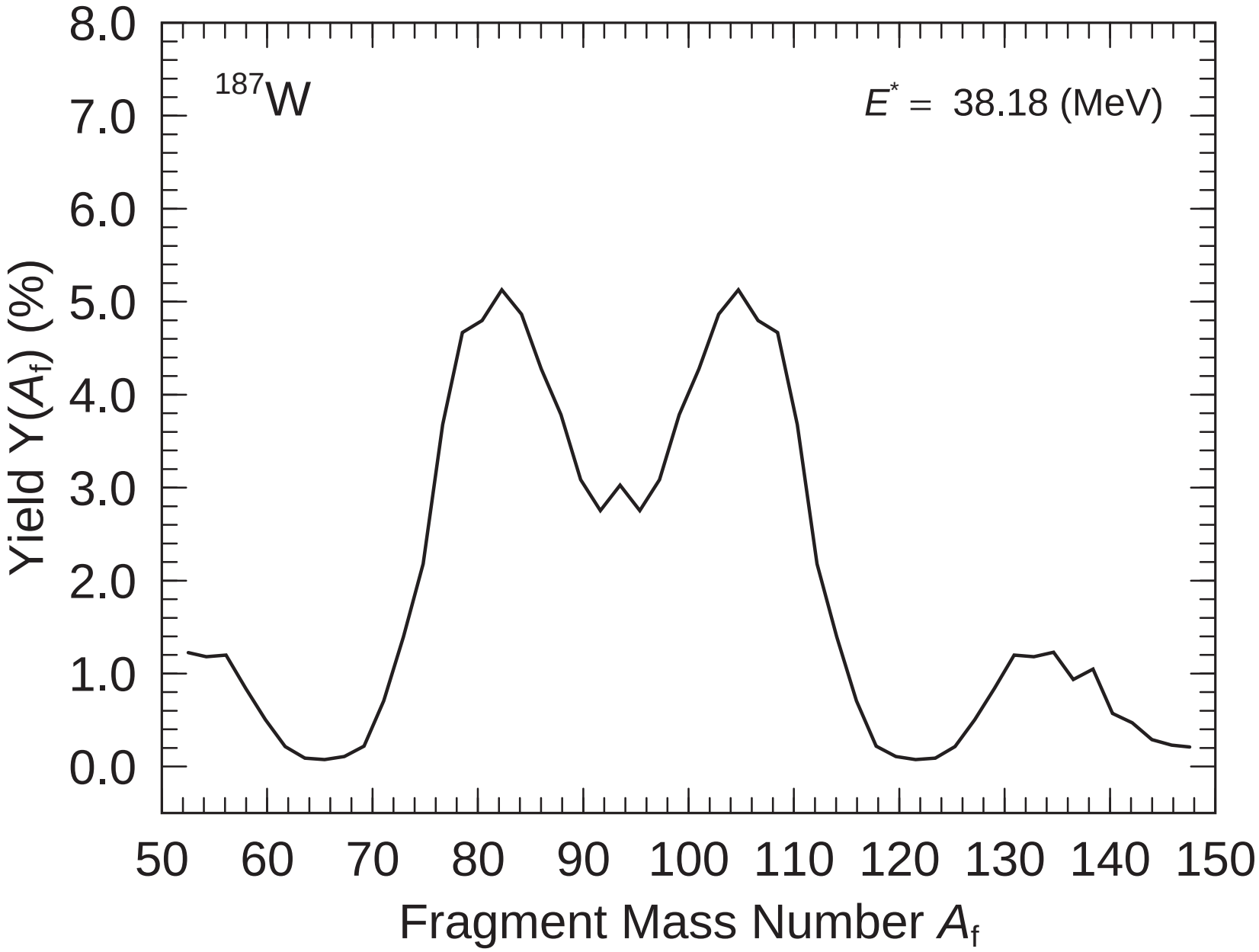

^{182}W
E^* = 36.42 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

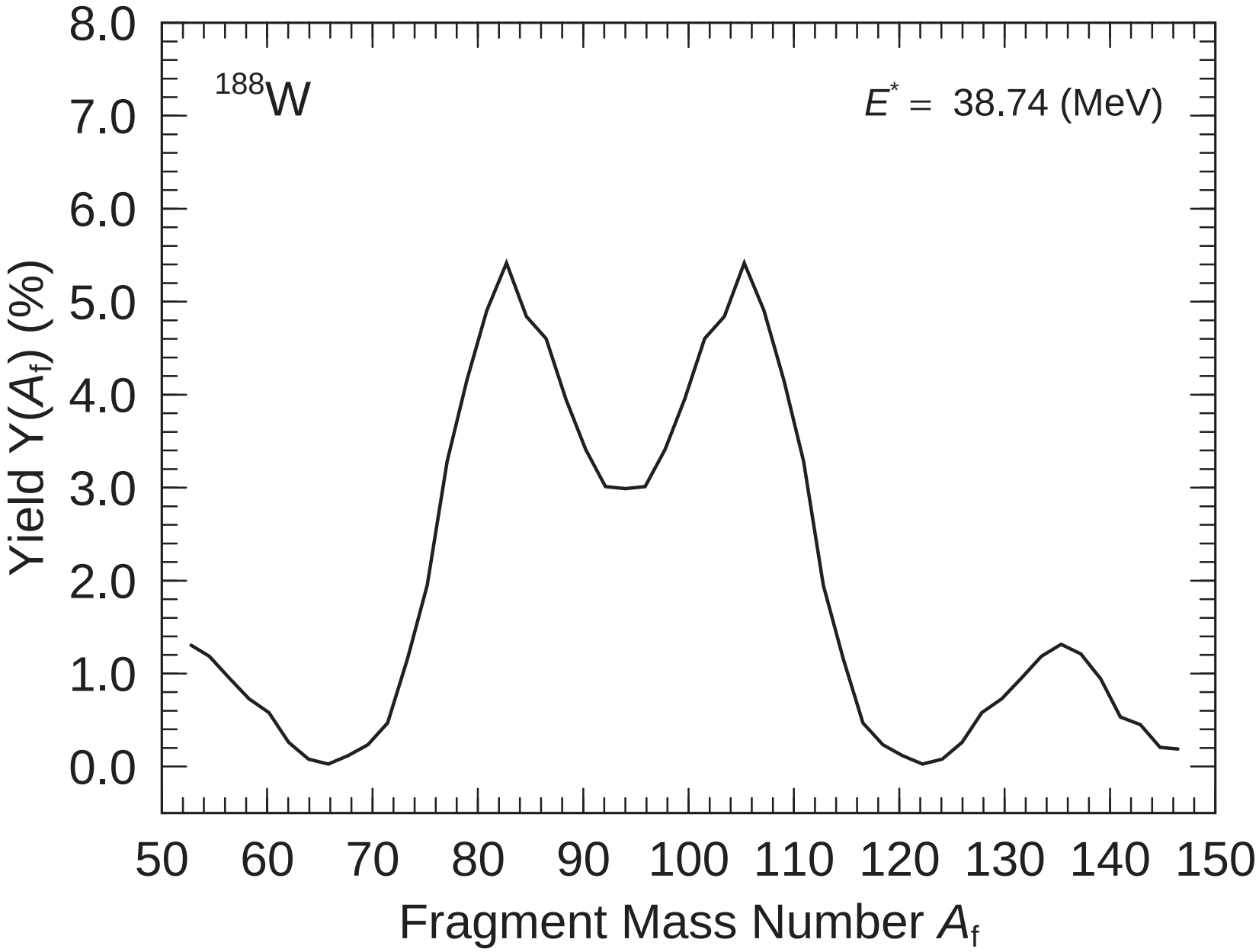

^{183}W
E^* = 36.92 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

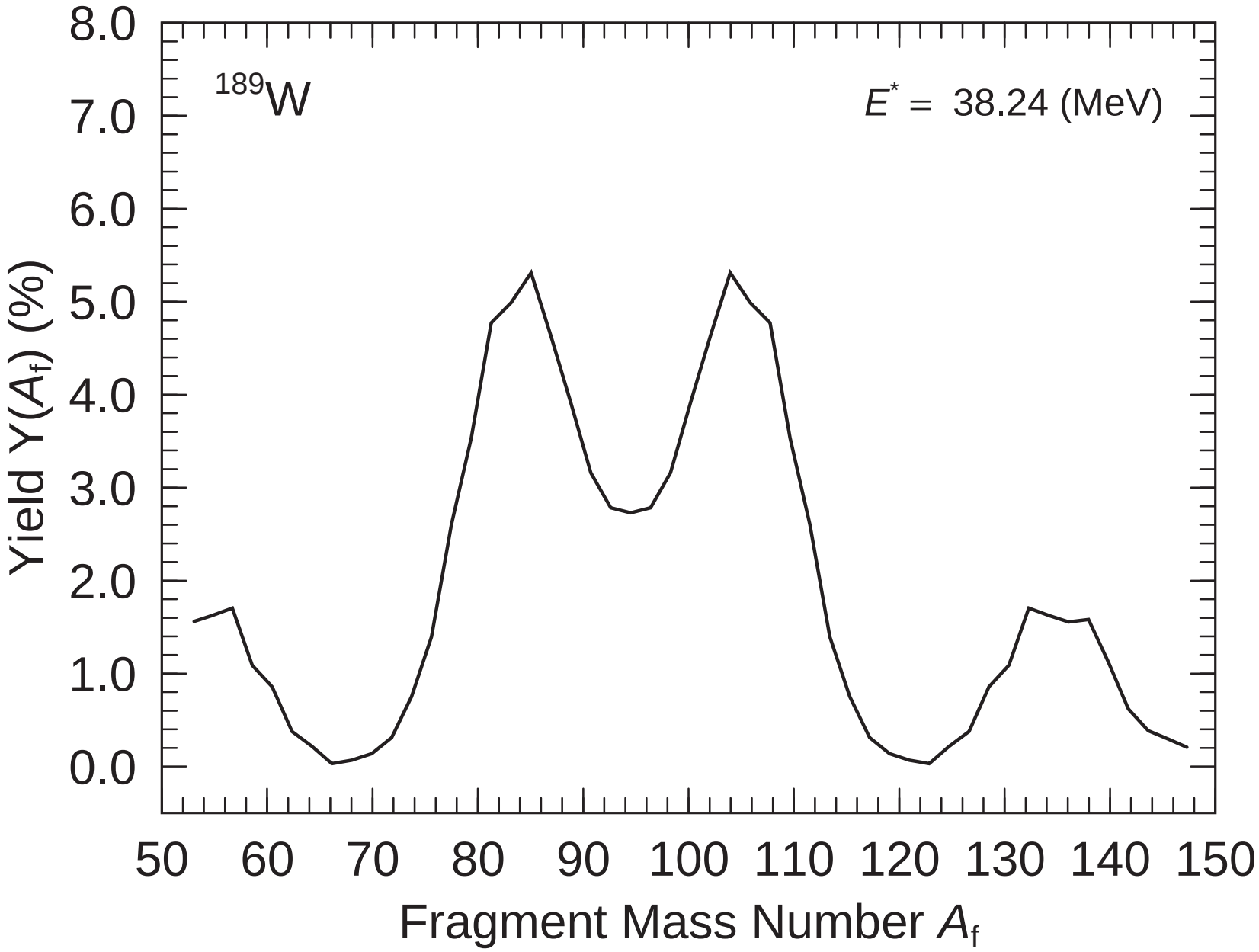

^{184}W
E^* = 36.70 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

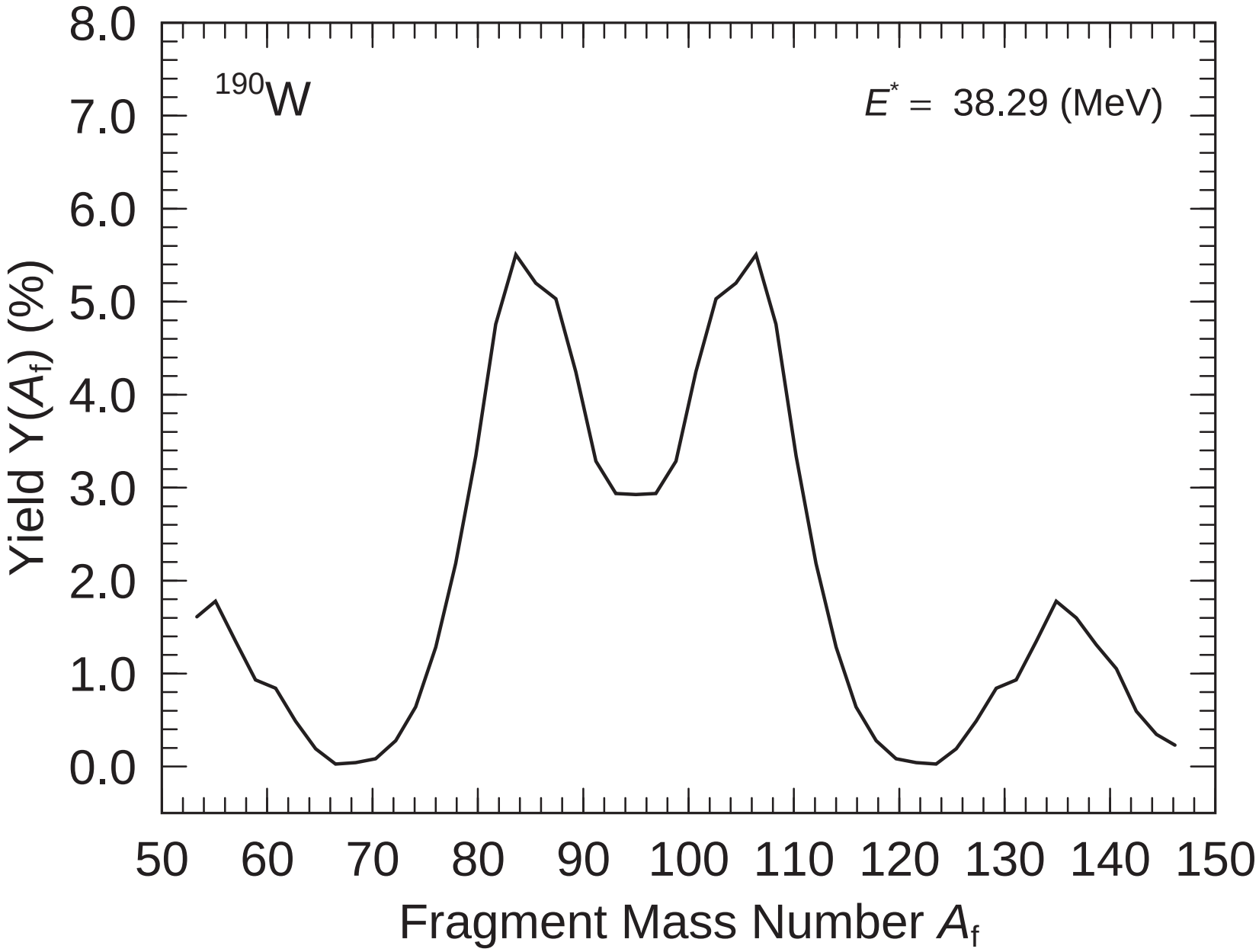

^{185}W
E^* = 37.13 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

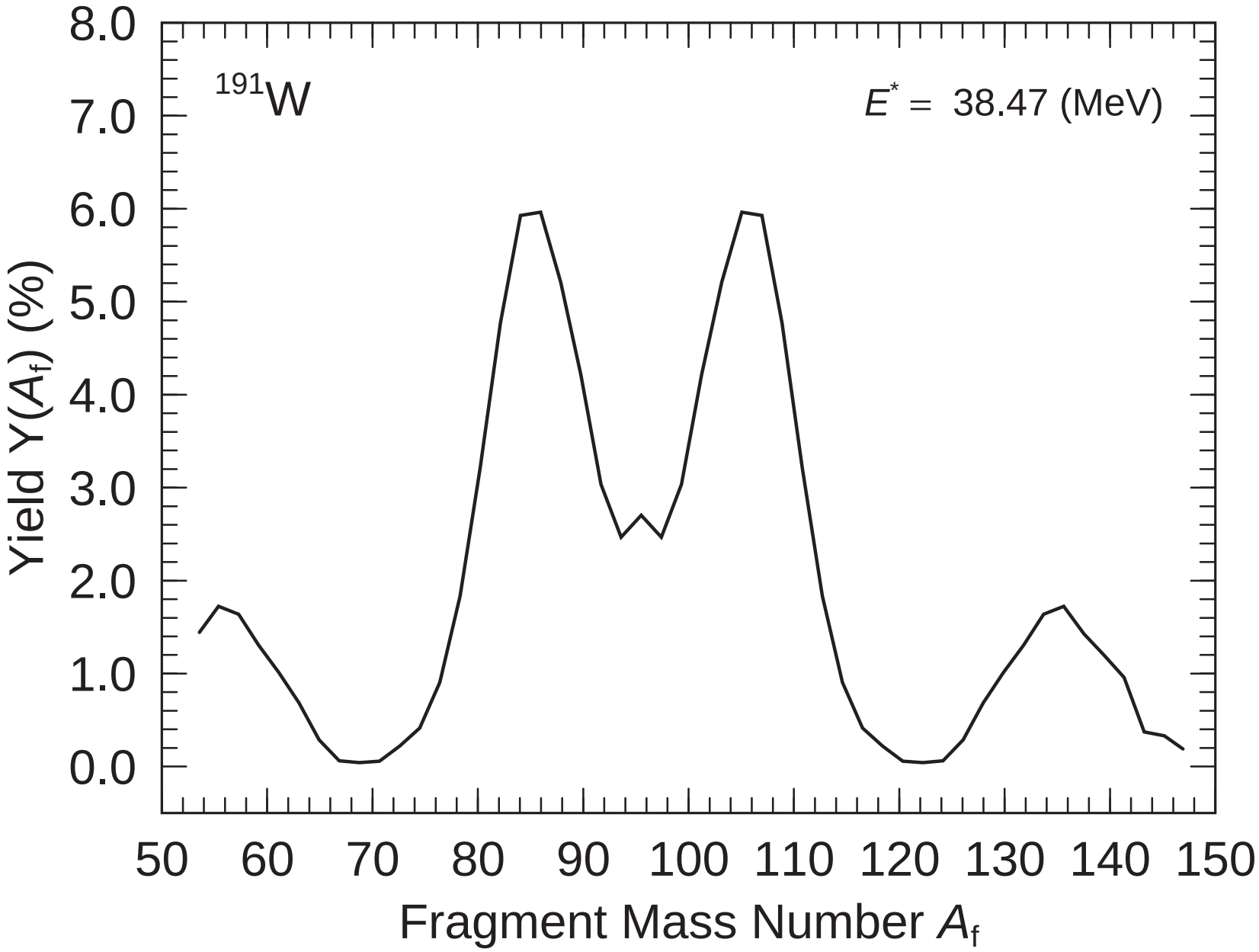

^{186}W
E^* = 37.37 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

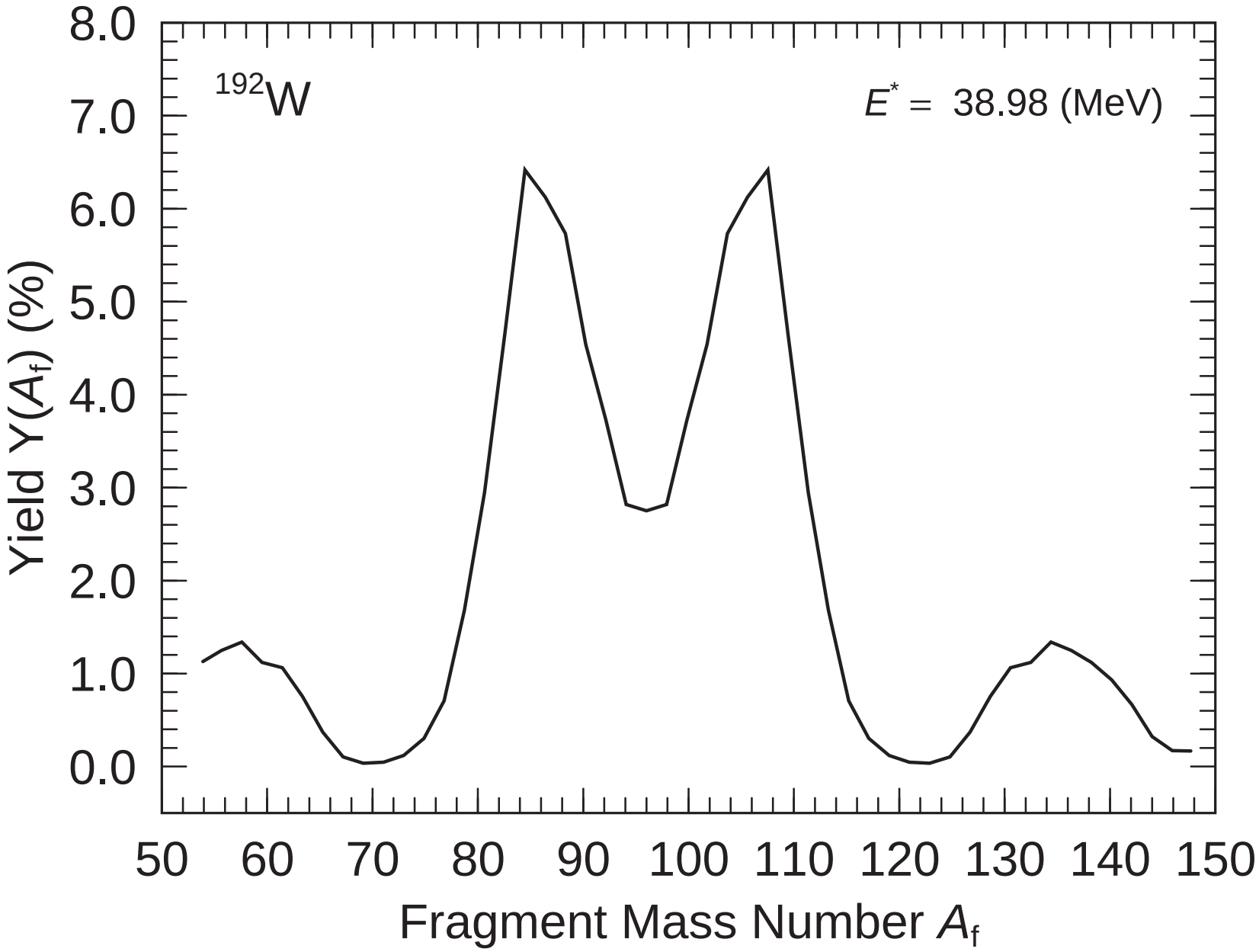

^{187}W
E^* = 38.18 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

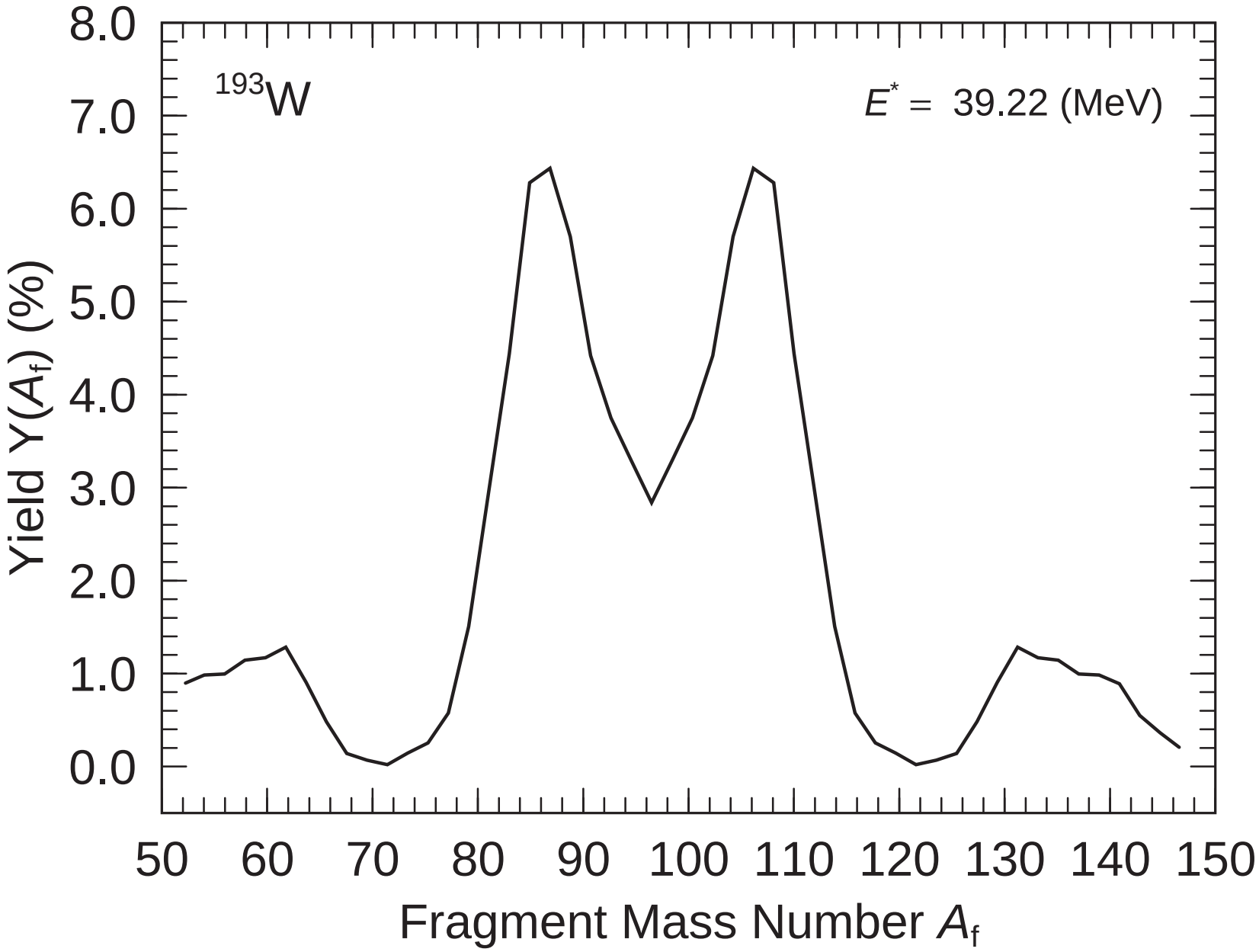

^{188}W
E^* = 38.74 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

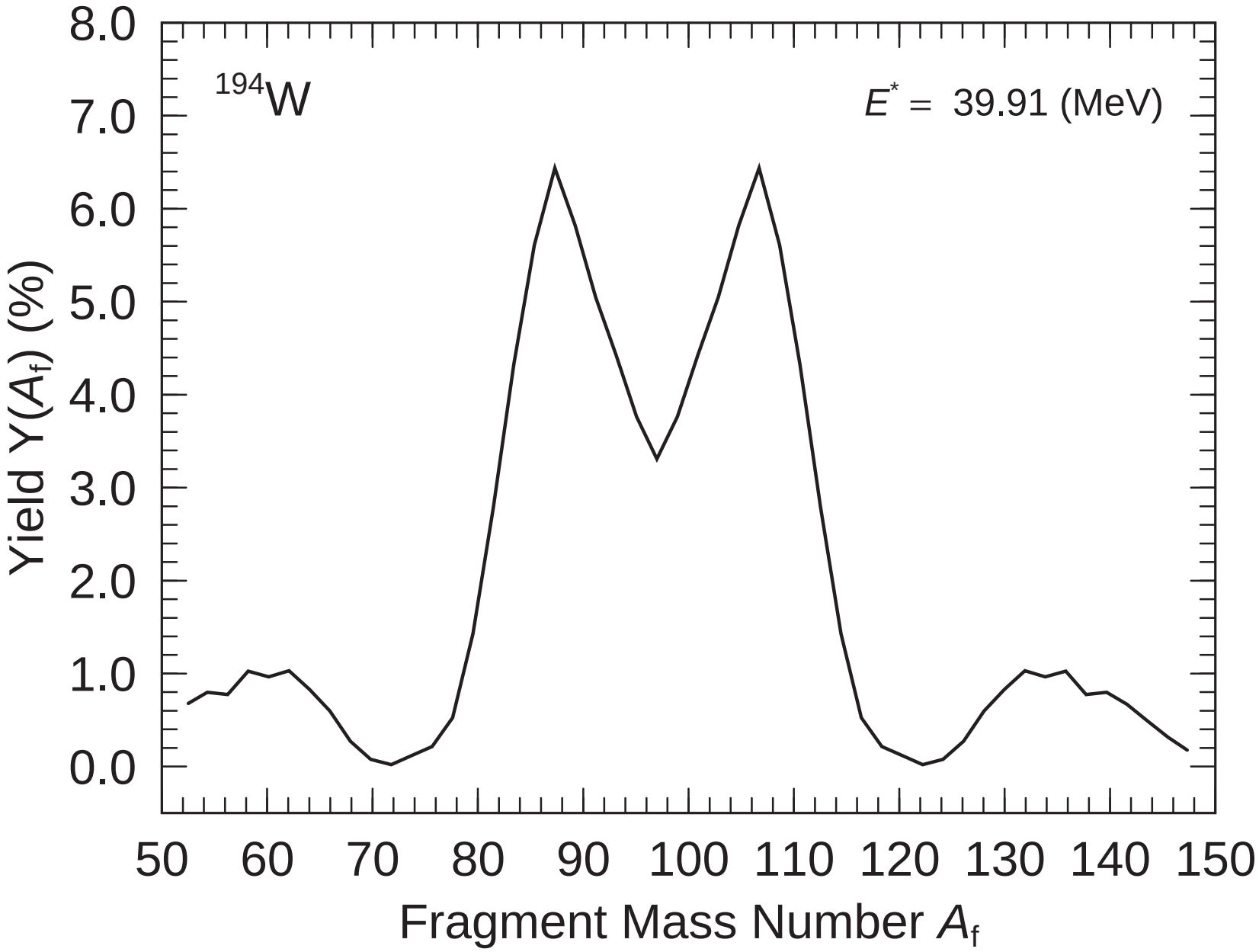

^{189}W
E^* = 38.24 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

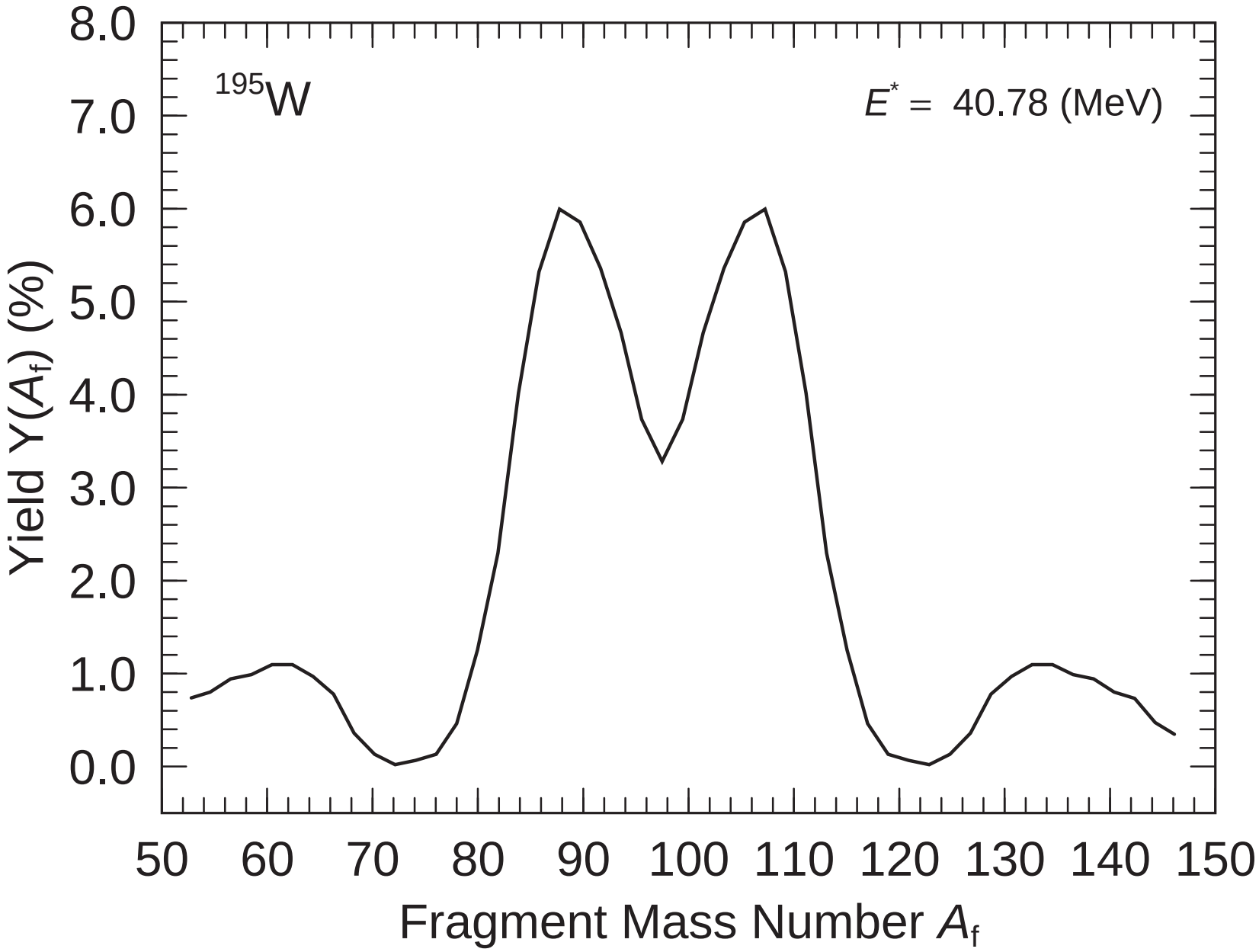

^{190}W
E^* = 38.29 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

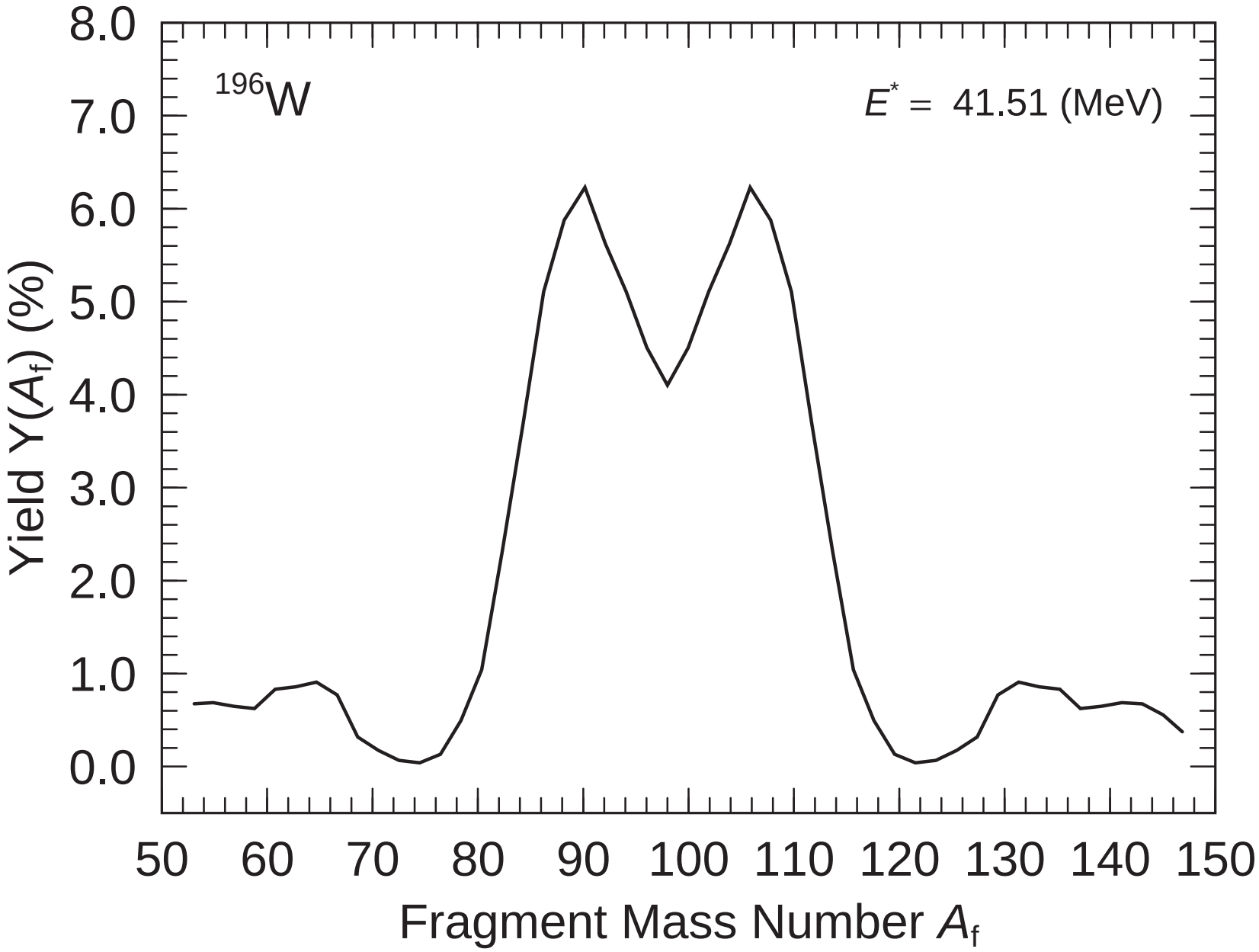

^{191}W
E^* = 38.47 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

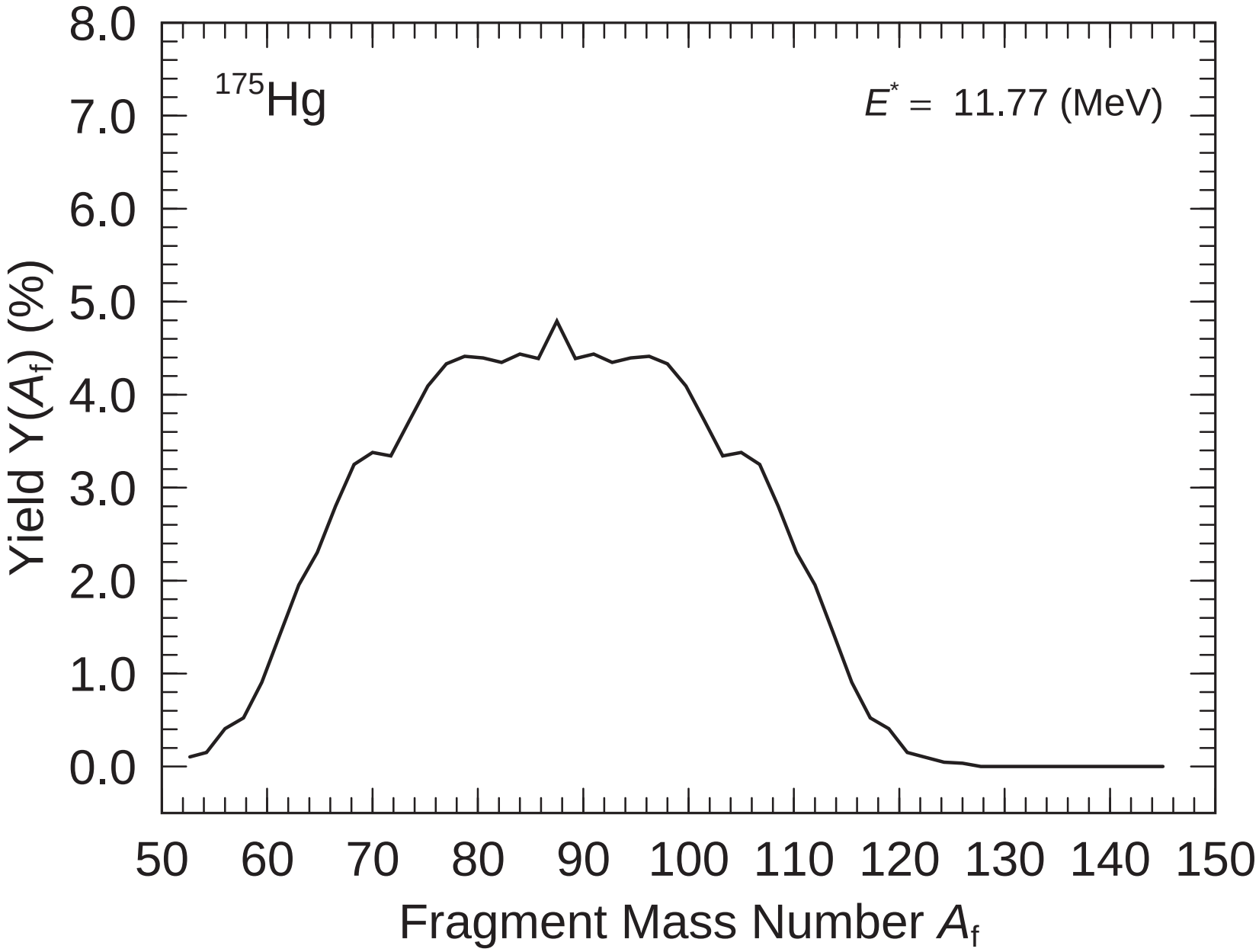

^{192}W
E^* = 38.98 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

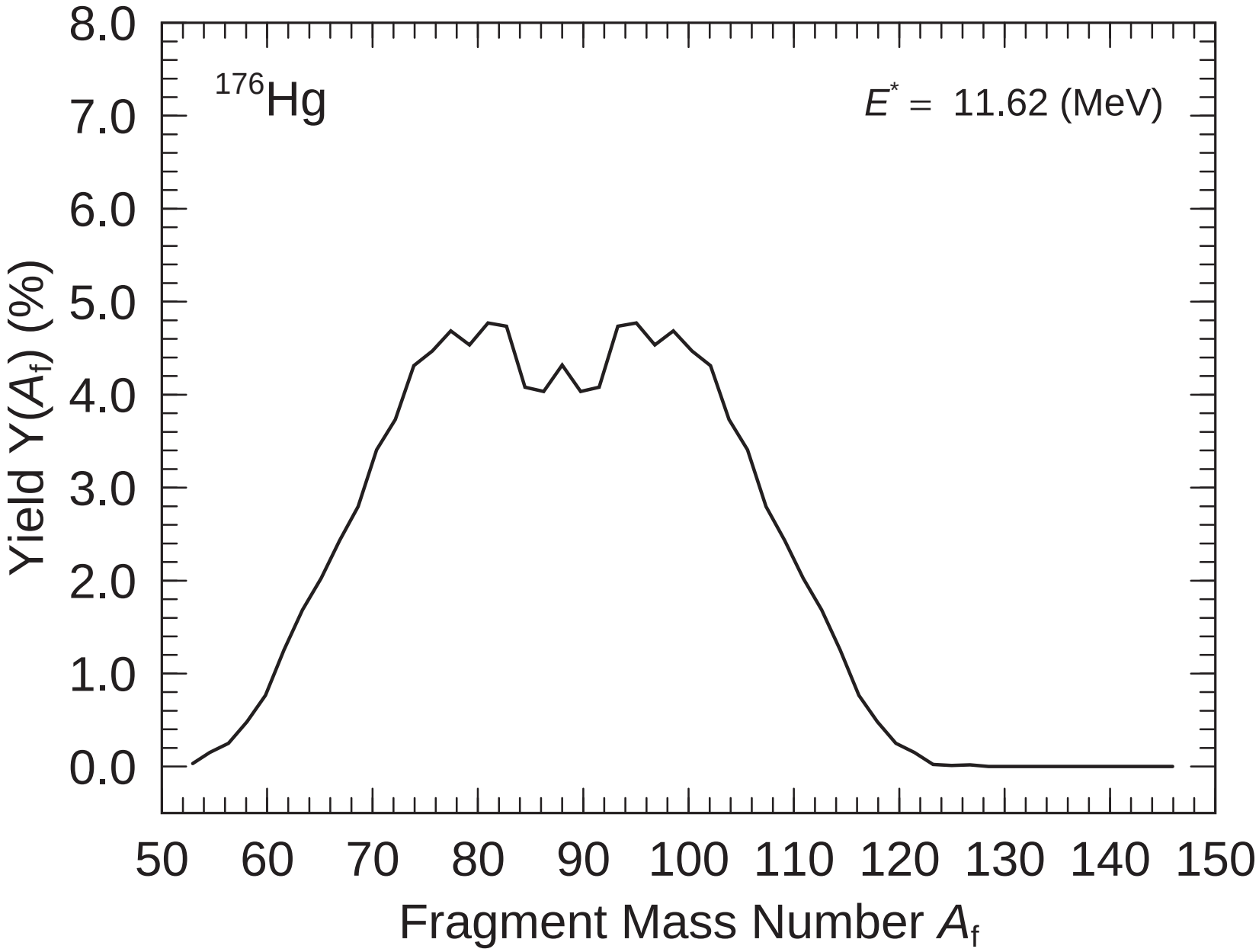

^{193}W
E^* = 39.22 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

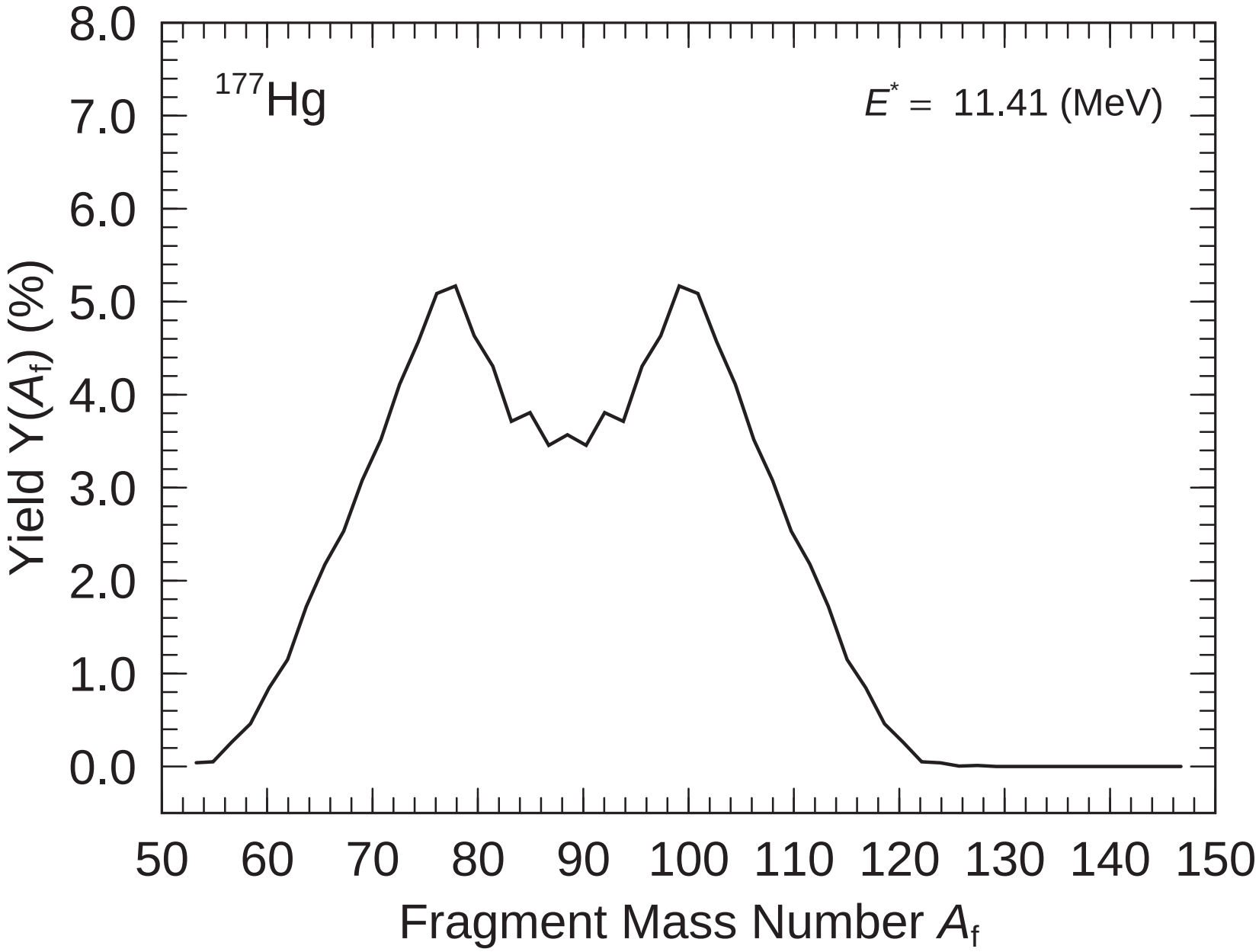

^{194}W
E^* = 39.91 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

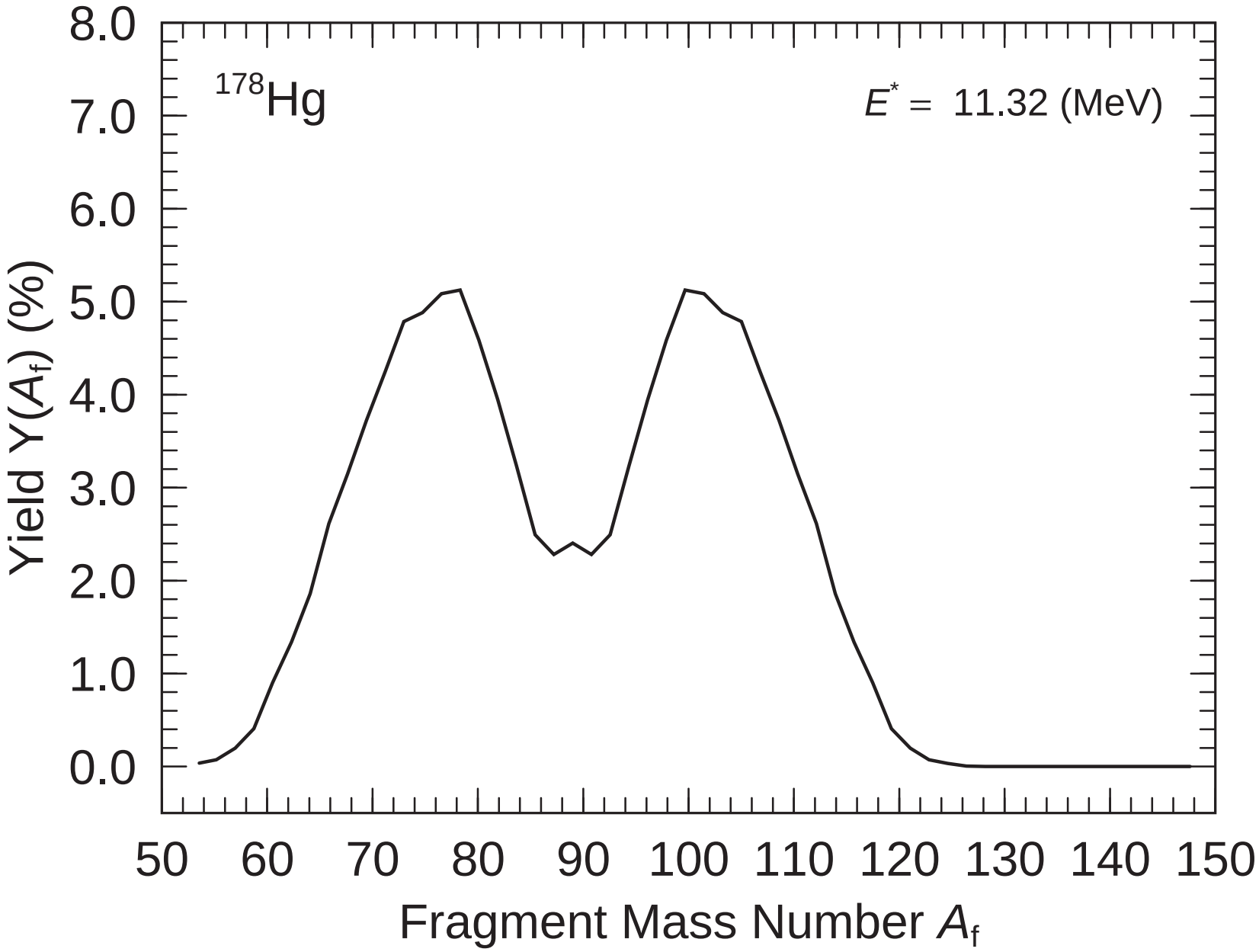

^{195}W
E^* = 40.78 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

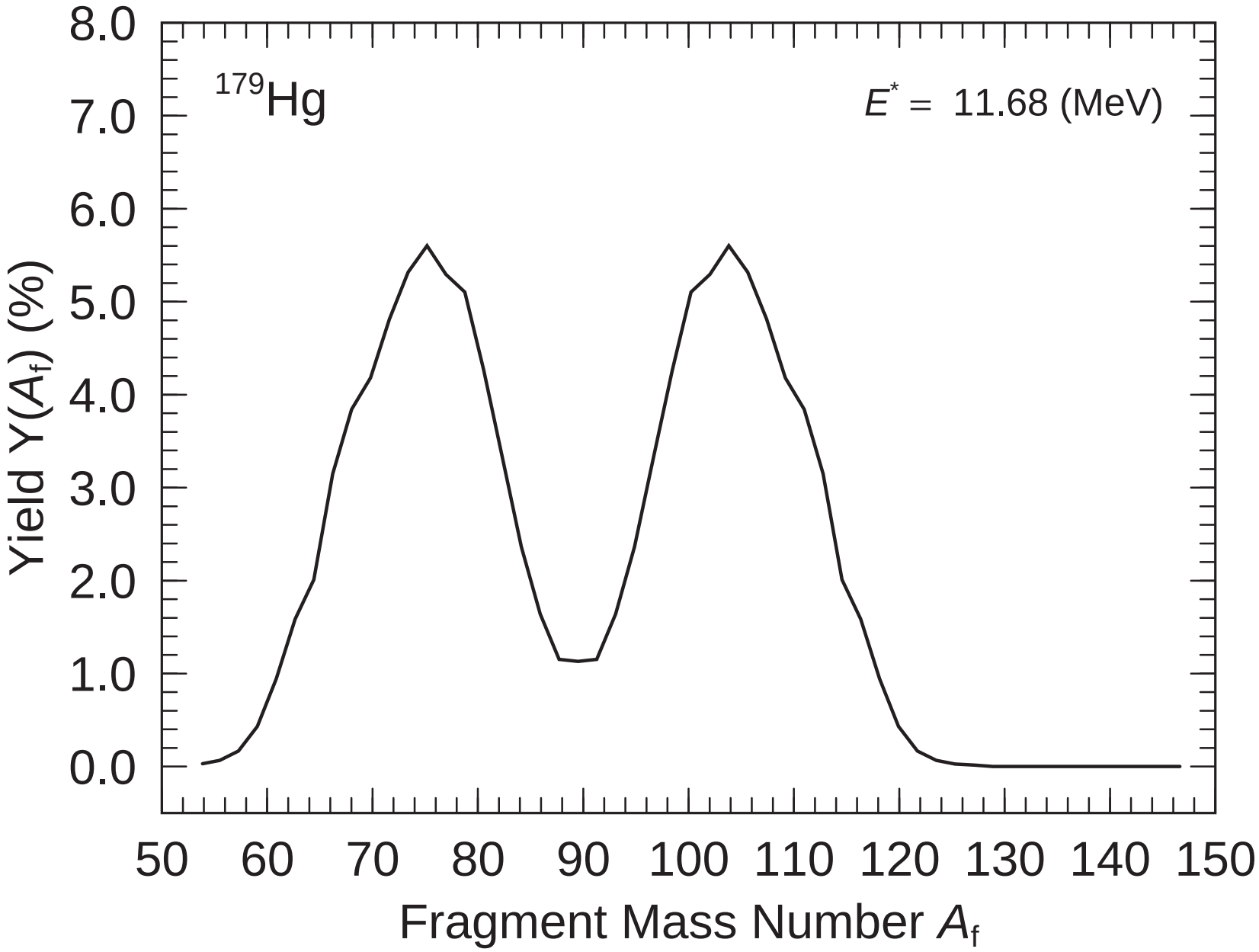

^{196}W
E^* = 41.51 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

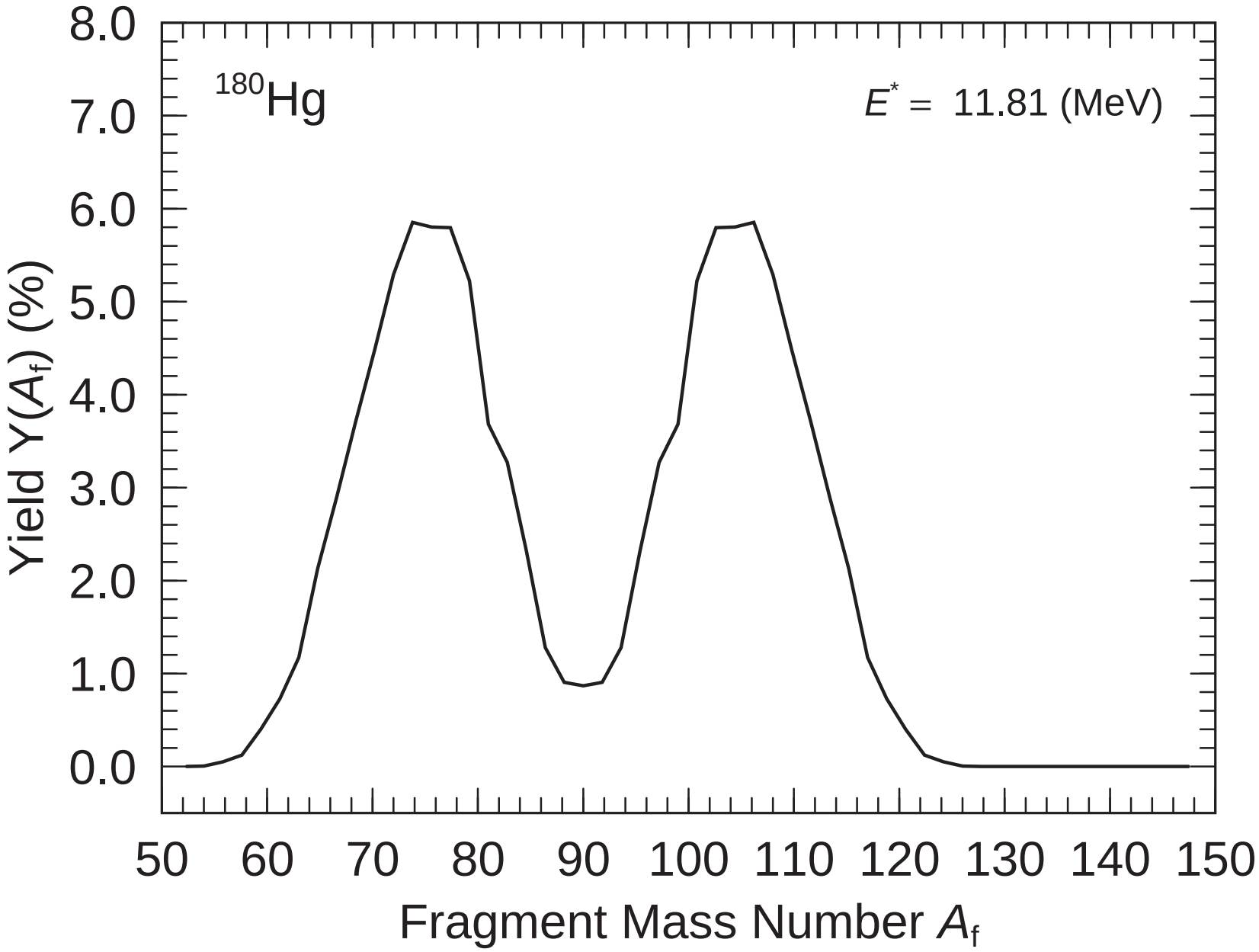

^{175}Hg
E^* = 11.77 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

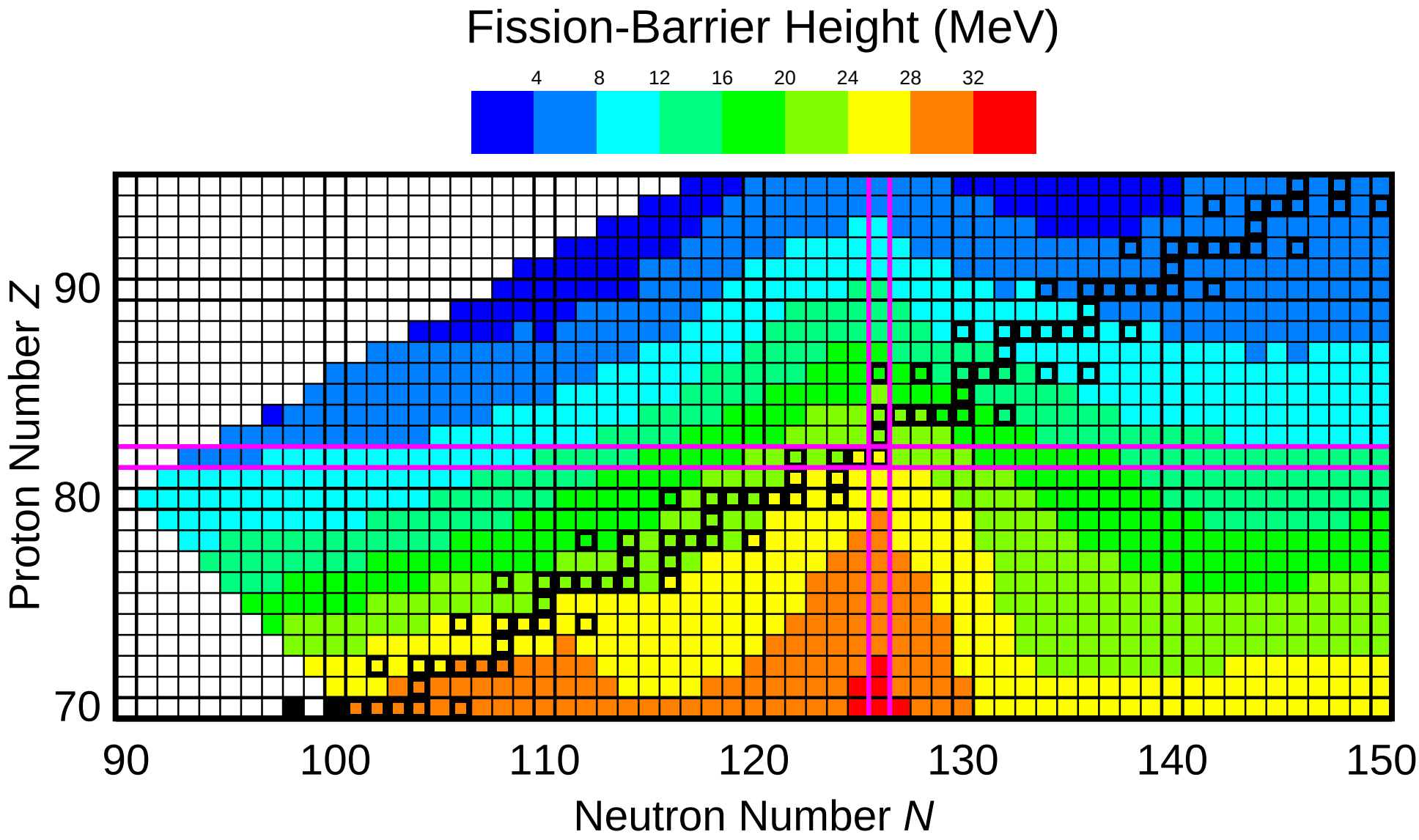

^{176}Hg
E^* = 11.62 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

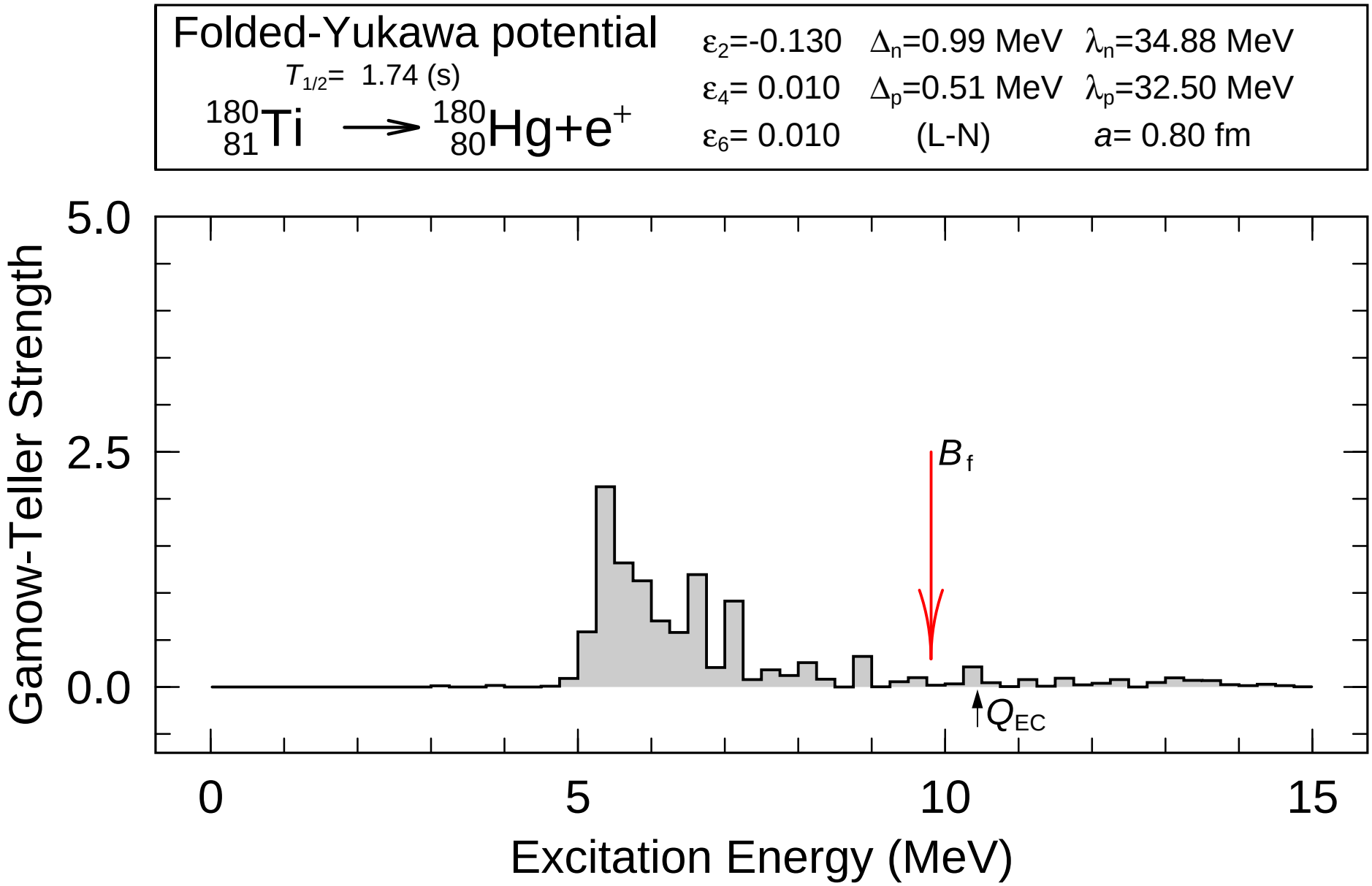

^{177}Hg
E^* = 11.41 (MeV)
Yield Y(A_f) (%)
Fragment Mass Number A_f
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150

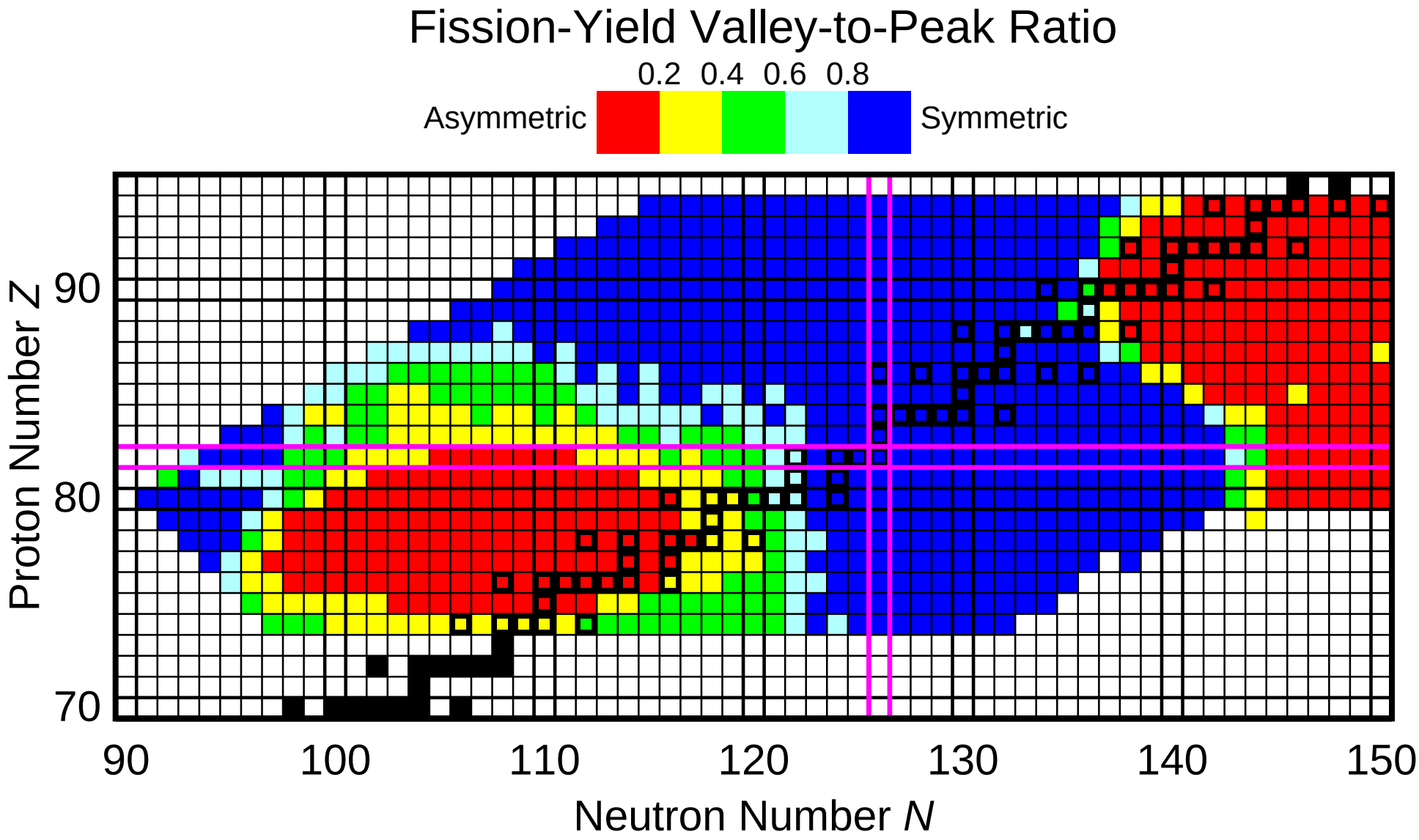

^{178}Hg
E^* = 11.32 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

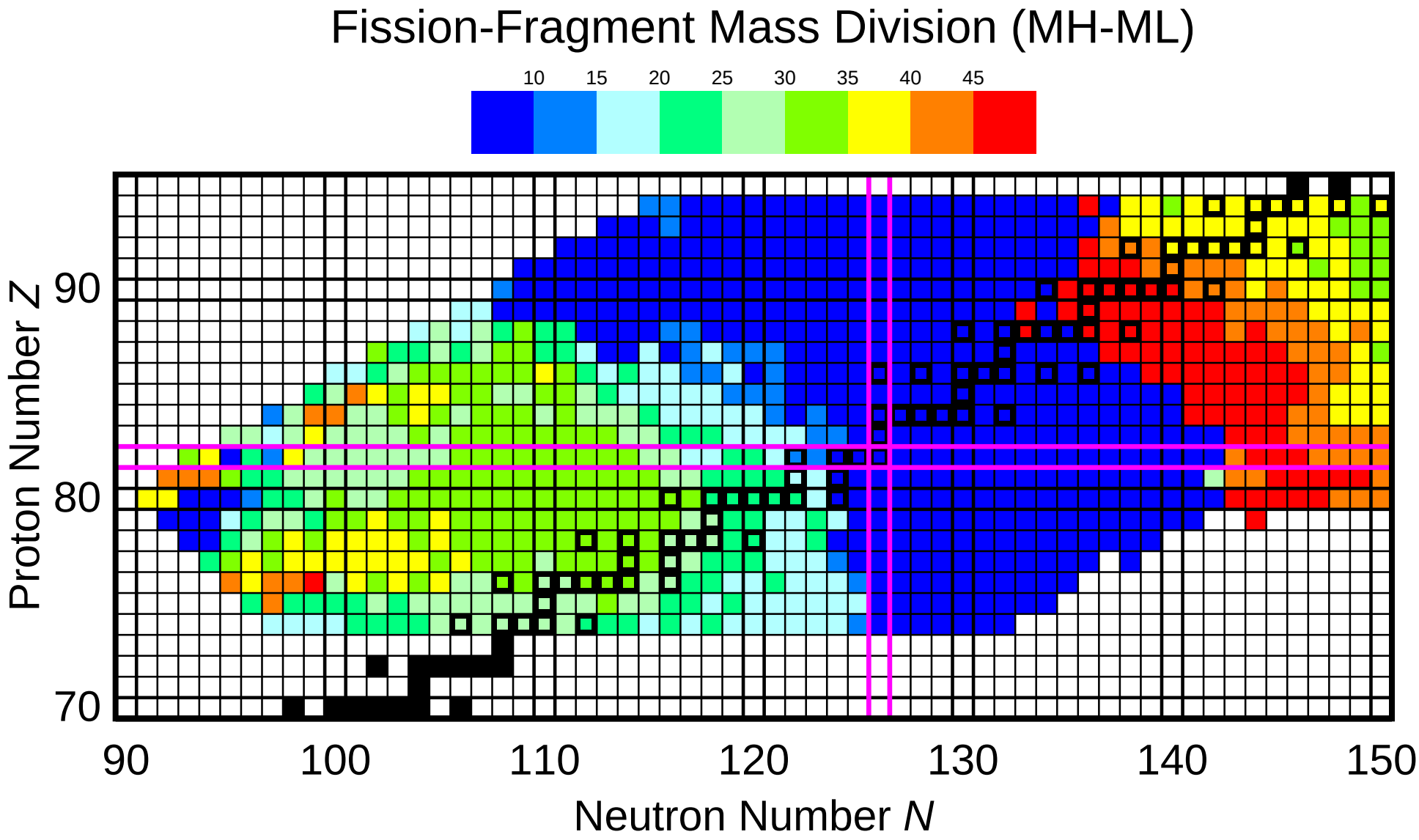

^{179}Hg
E^* = 11.68 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f


^{180}Hg
E^* = 11.81 (MeV)
Yield Y(A_f) (%)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
50
60
70
80
90
100
110
120
130
140
150
Fragment Mass Number A_f

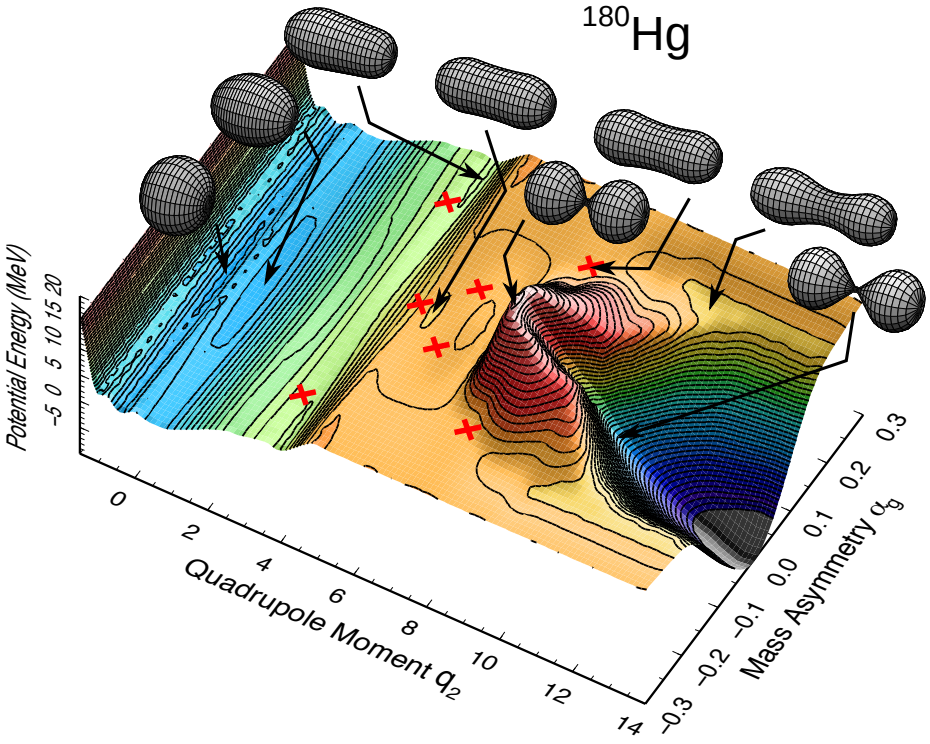

Fission-Barrier Height (MeV)
4
8
12
16
20
24
28
32
Proton Number Z
90
80
70
90
100
110
120
130
140
150
Neutron Number N

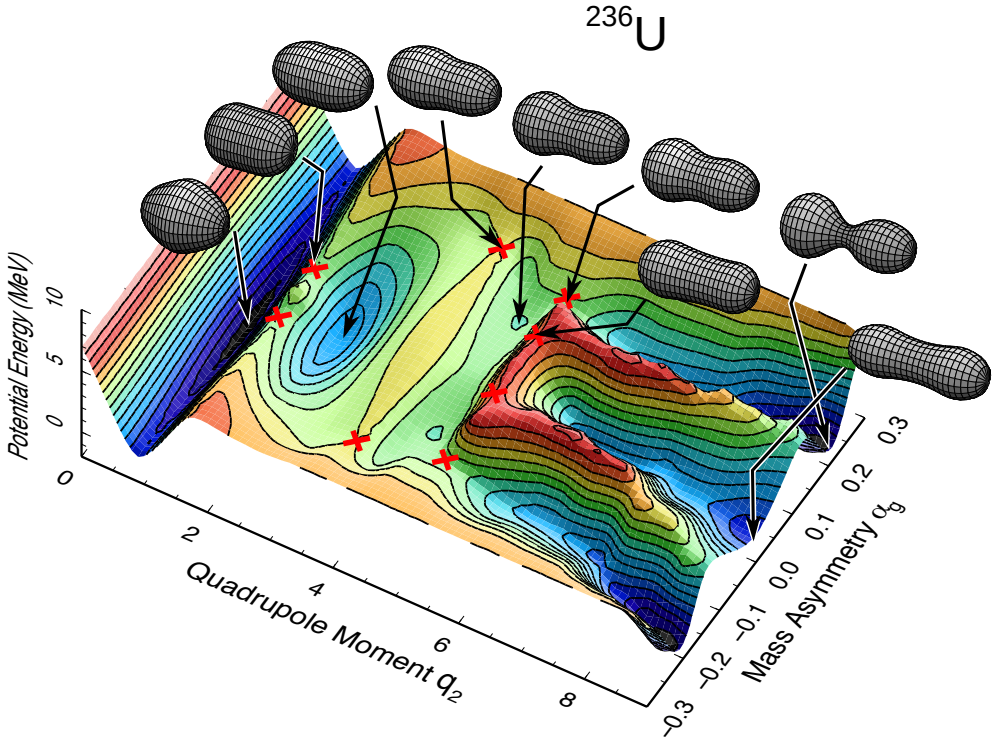

Folded-Yukawa potential
$T_{1/2}$= 1.74 (s)
$^{180}_{81}Ti \rightarrow {}^{180}_{80}Hg+e^{+}$
ε_2=-0.130
ε_4= 0.010
ε_6= 0.010
Δ_n=0.99 MeV
Δ_p=0.51 MeV
(L-N)
λ_n=34.88 MeV
λ_p=32.50 MeV
a= 0.80 fm
Gamow-Teller Strength
5.0
2.5
0.0
B_f
Q_{EC}
0
5
10
15
Excitation Energy (MeV)


Fission-Yield Valley-to-Peak Ratio
0.2 0.4 0.6 0.8
Asymmetric
Symmetric
Proton Number Z
90
80
70
90
100
110
120
130
140
150
Neutron Number N

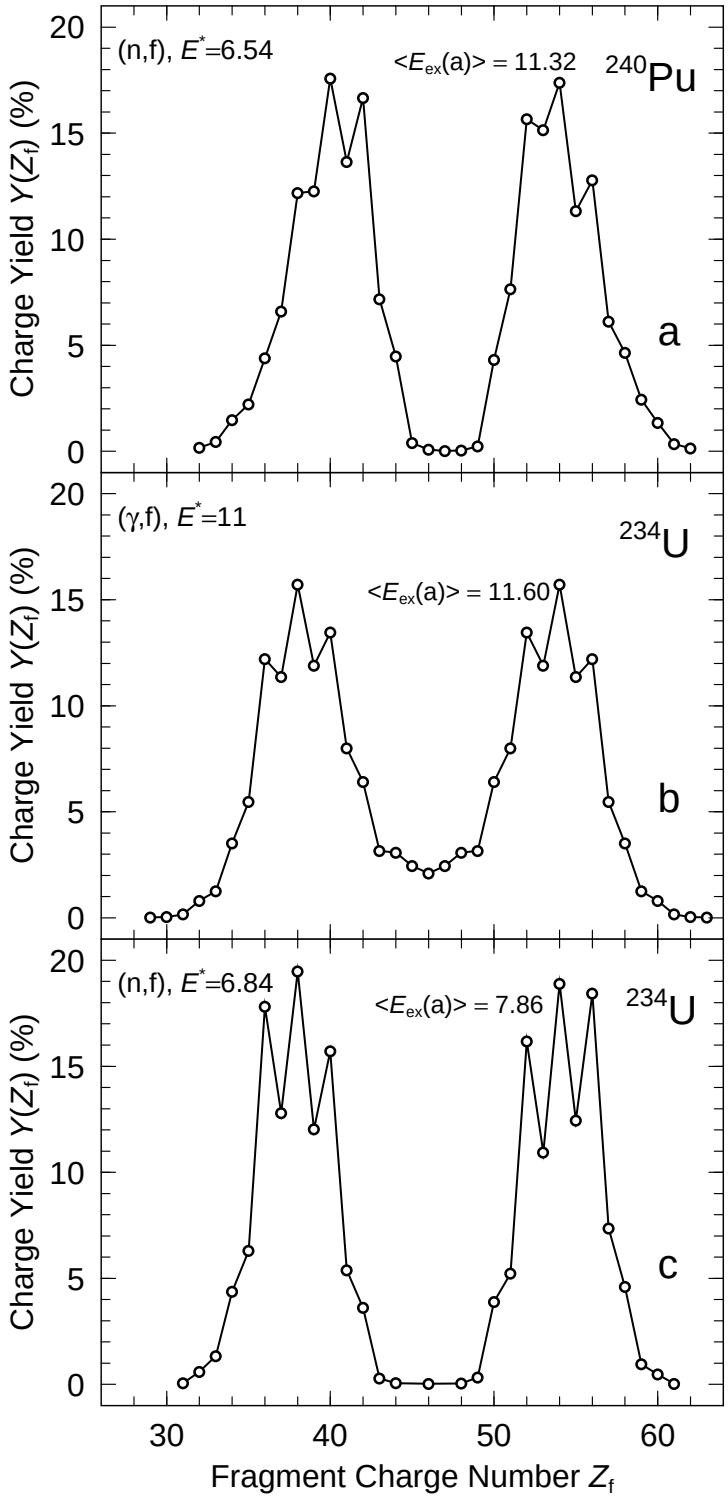

Fission-Fragment Mass Division (MH-ML)
10
15
20
25
30
35
40
45
Proton Number Z
90
80
70
90
100
110
120
130
140
150
Neutron Number N

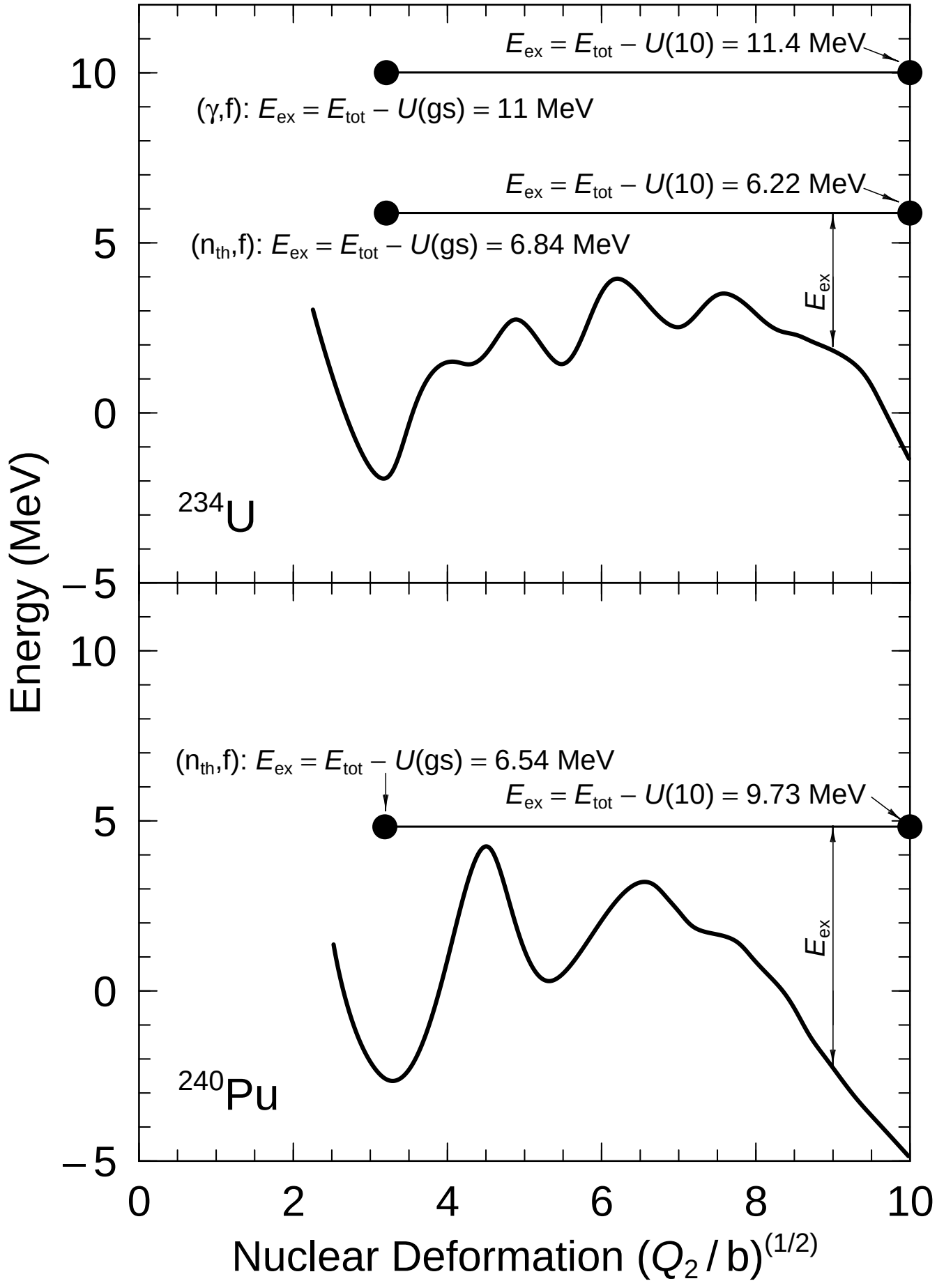
Contrasting Fission Potential-Energy Surfaces Hg↔U

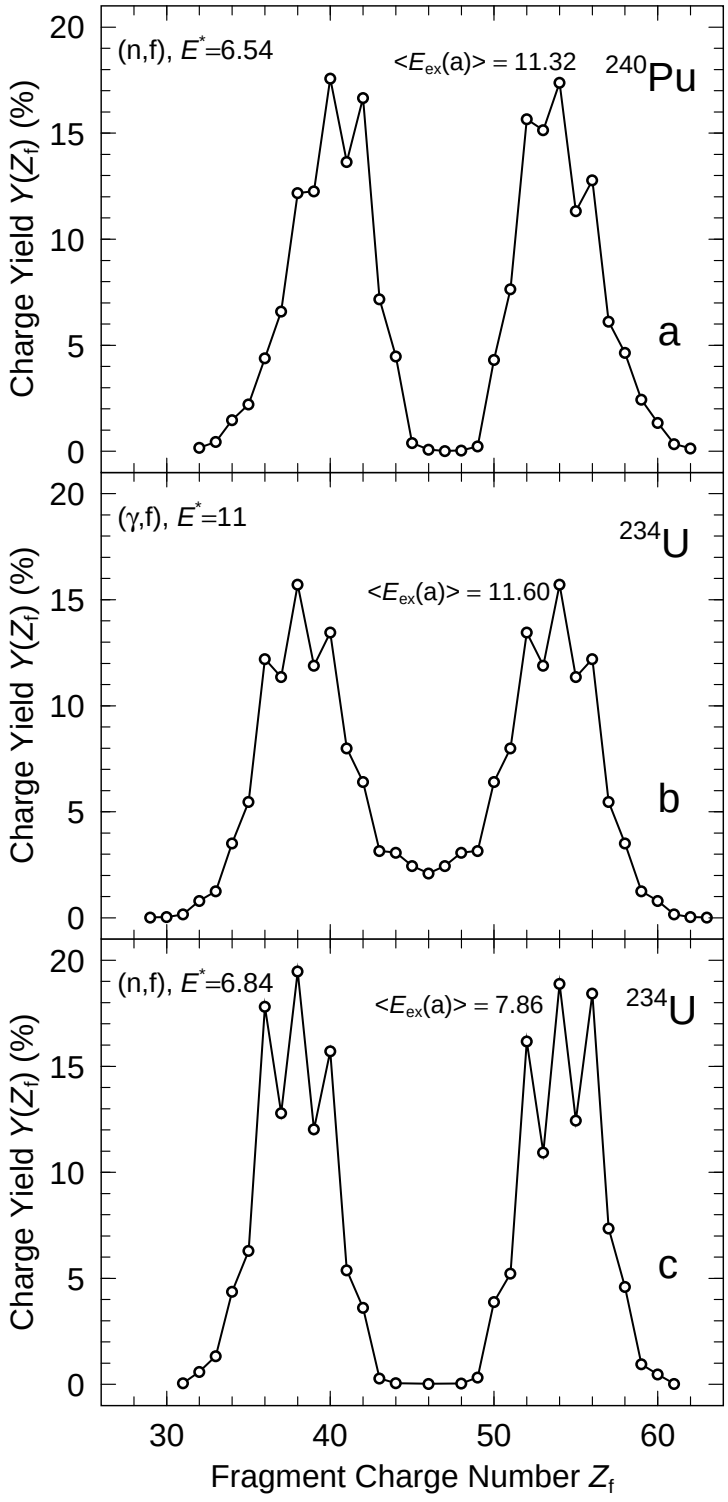


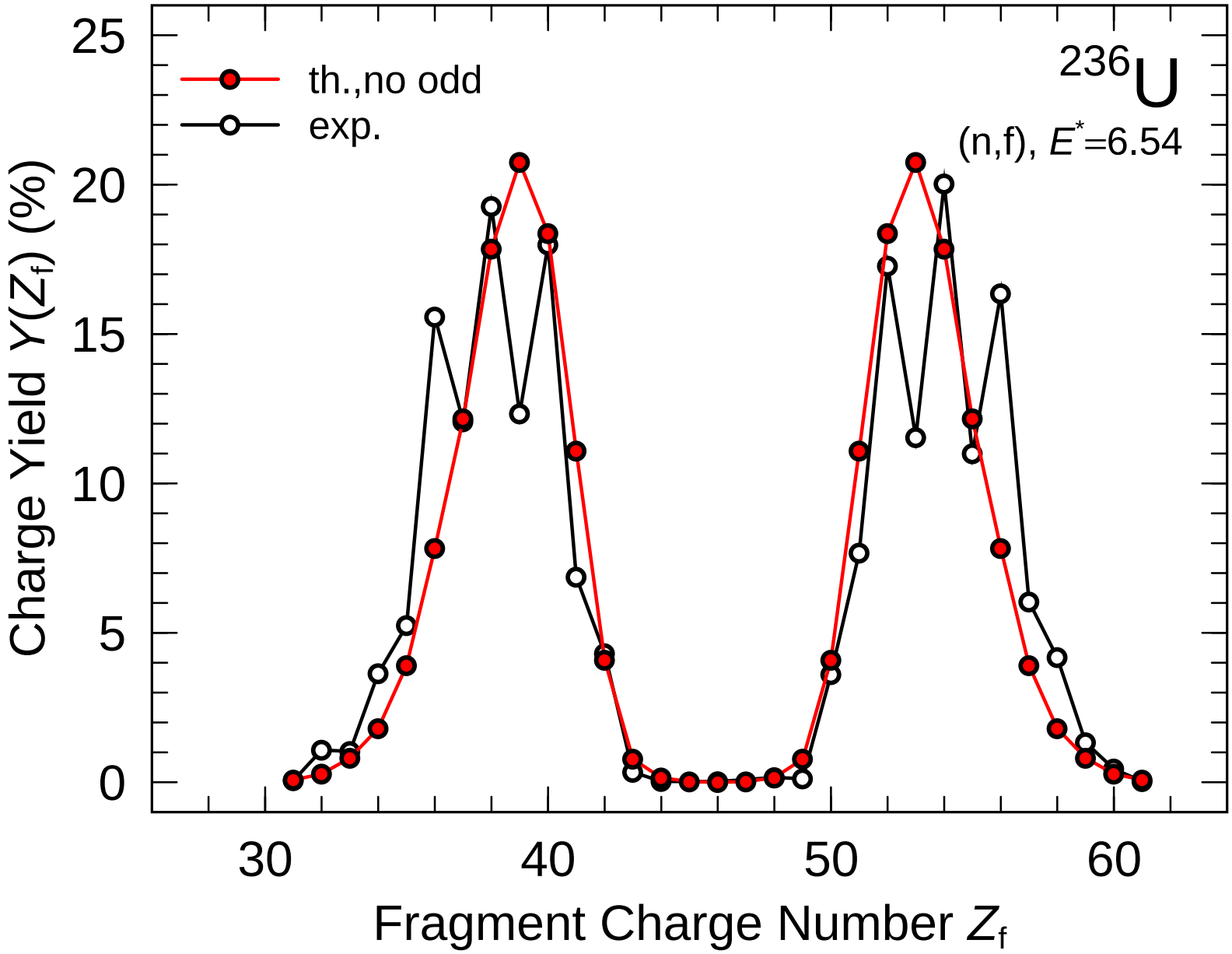


Ichikawa et al., PRC 86 024610 (2012)

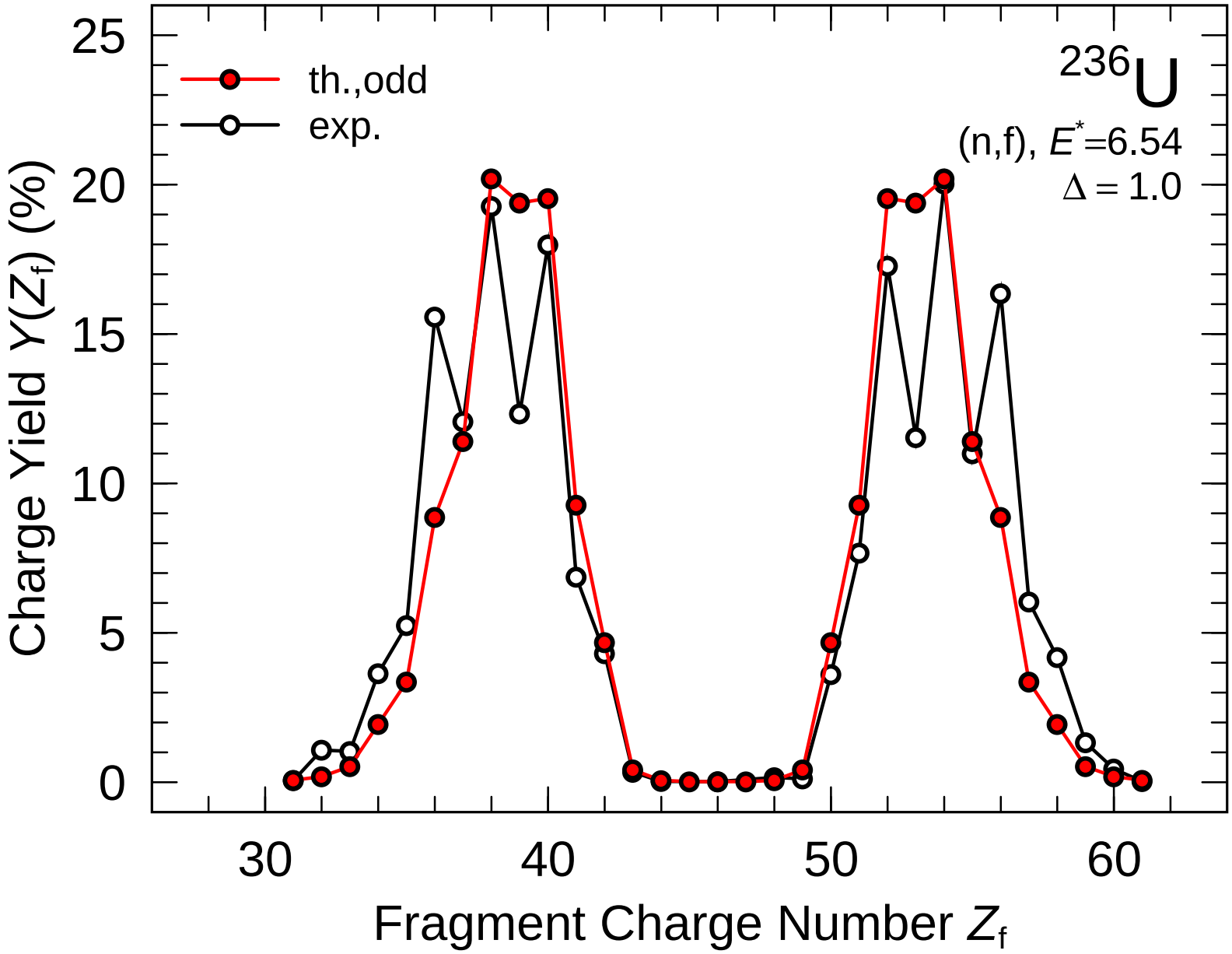

(n,f), E^*=6.54
<E_{ex}(a)> = 11.32
^{240}Pu
a
(γ,f), E^*=11
^{234}U
<E_{ex}(a)> = 11.60
b
(n,f), E^*=6.84
<E_{ex}(a)> = 7.86
^{234}U
c
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
30
40
50
60

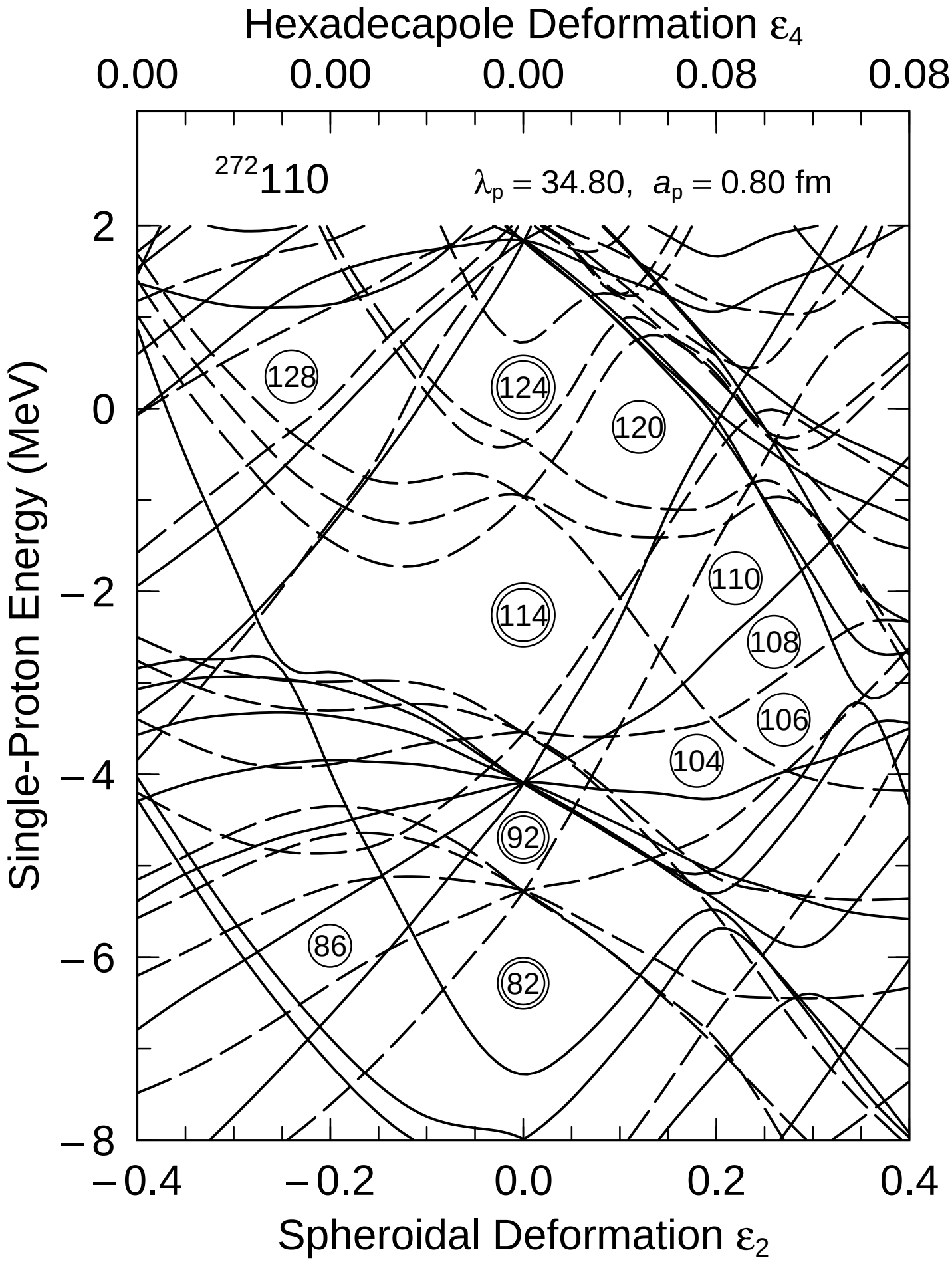

$E_{ex} = E_{tot} - U(10) = 11.4$ MeV
(γ,f): $E_{ex} = E_{tot} - U(gs) = 11$ MeV
$E_{ex} = E_{tot} - U(10) = 6.22$ MeV
(n_{th},f): $E_{ex} = E_{tot} - U(gs) = 6.84$ MeV
E_{ex}
^{234}U
(n_{th},f): $E_{ex} = E_{tot} - U(gs) = 6.54$ MeV
$E_{ex} = E_{tot} - U(10) = 9.73$ MeV
E_{ex}
^{240}Pu
Energy (MeV)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

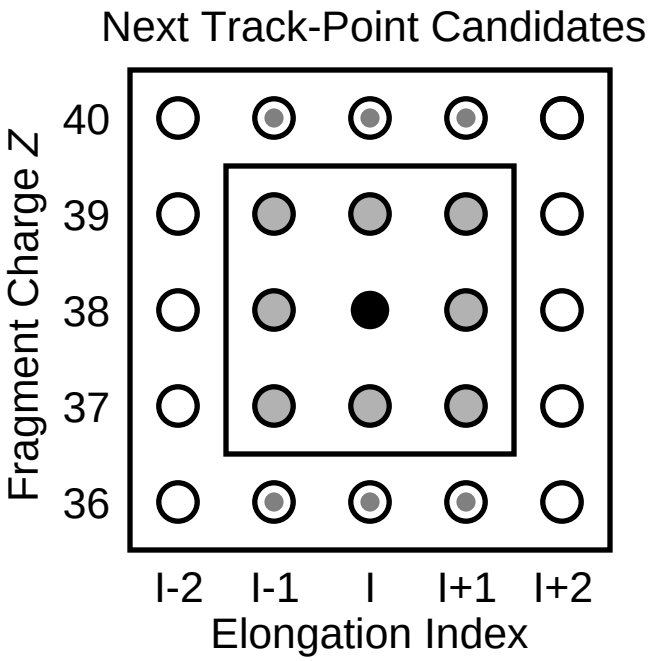

(n,f), E^*=6.54
<E_{ex}(a)> = 11.32
^{240}Pu
a
(γ,f), E^*=11
^{234}U
<E_{ex}(a)> = 11.60
b
(n,f), E^*=6.84
<E_{ex}(a)> = 7.86
^{234}U
c
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
30
40
50
60

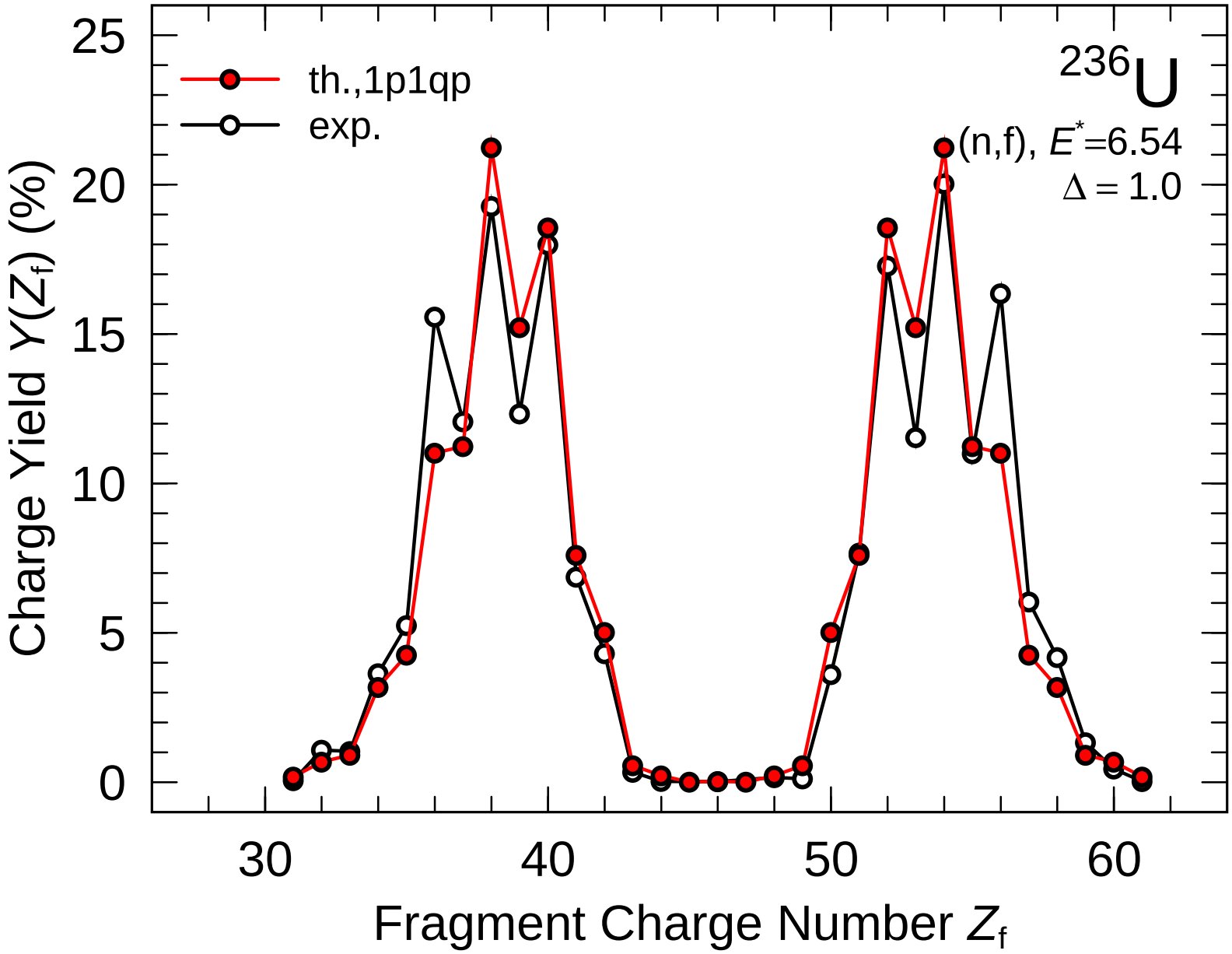

th.,no odd
exp.
^{236}U
(n,f), E^*=6.54
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

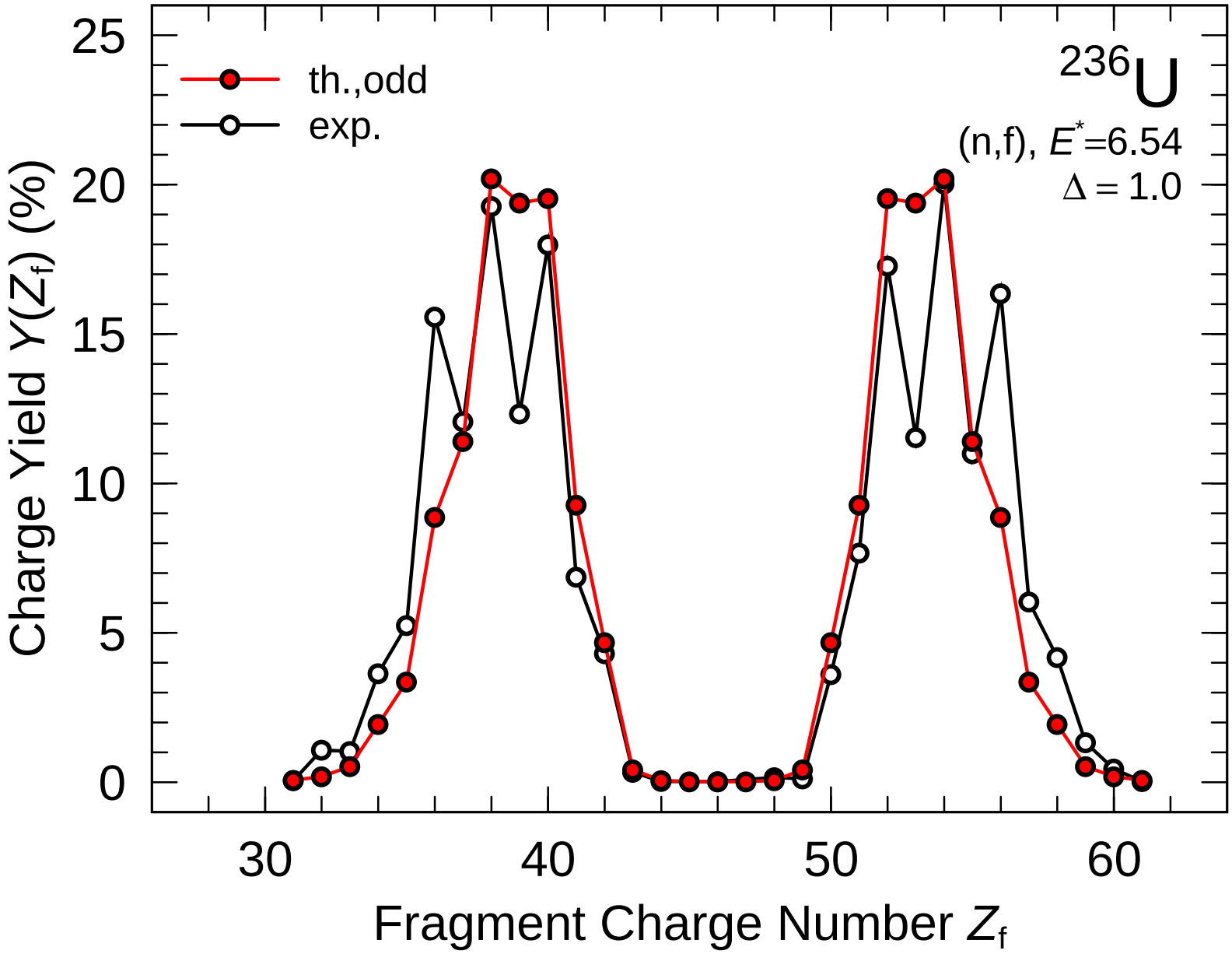
```
READ(LU,'(2f10.3)') r,rw

idiv =(N+1)/2
if(N+1 .eq. 2*idiv) r = r + (rw-1 +0.01)*2*1.0

E(I,J,K,L,N) = r
```

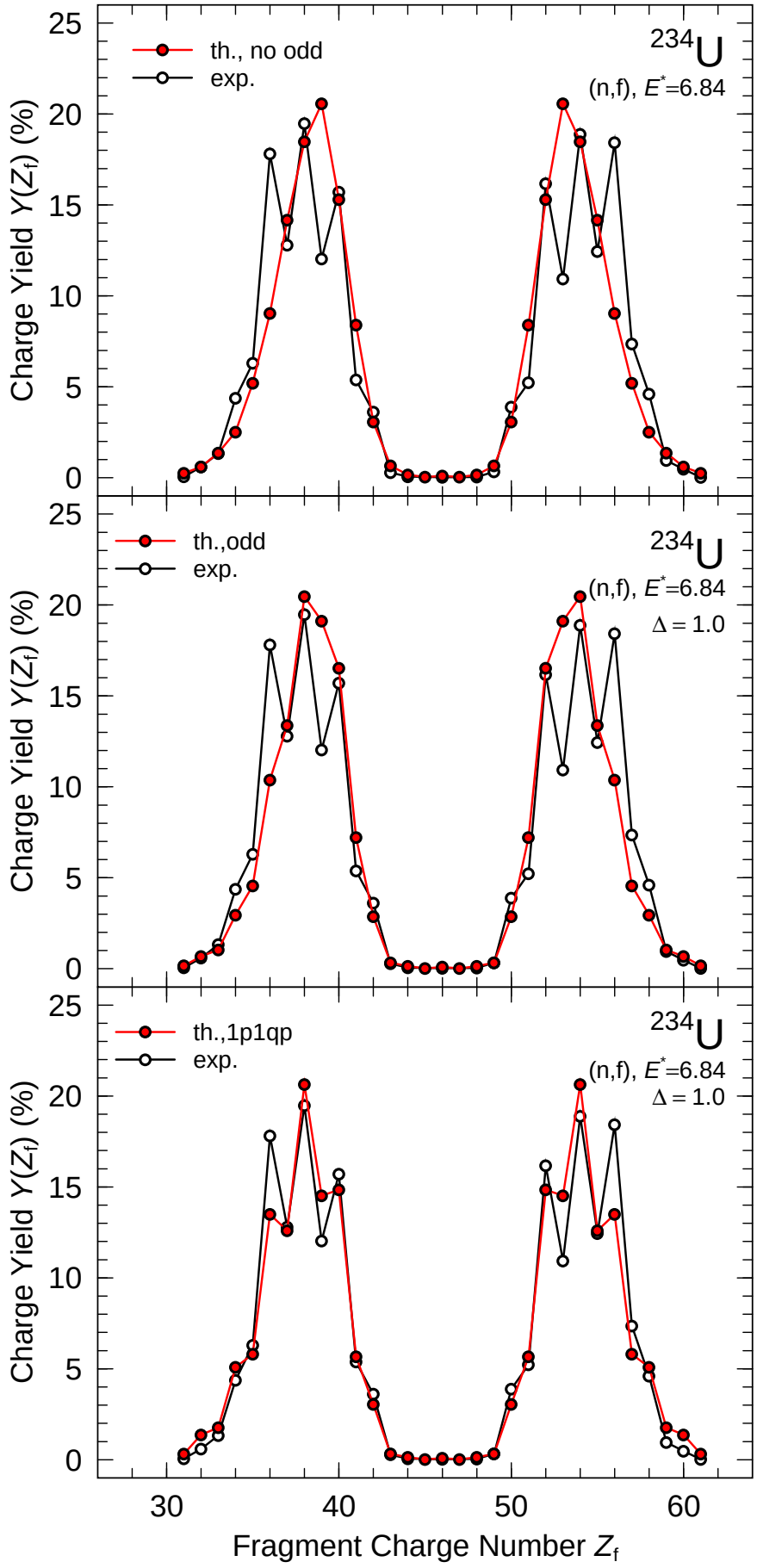

th.,odd
exp.
^{236}U
(n,f), E^*=6.54
Δ = 1.0
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

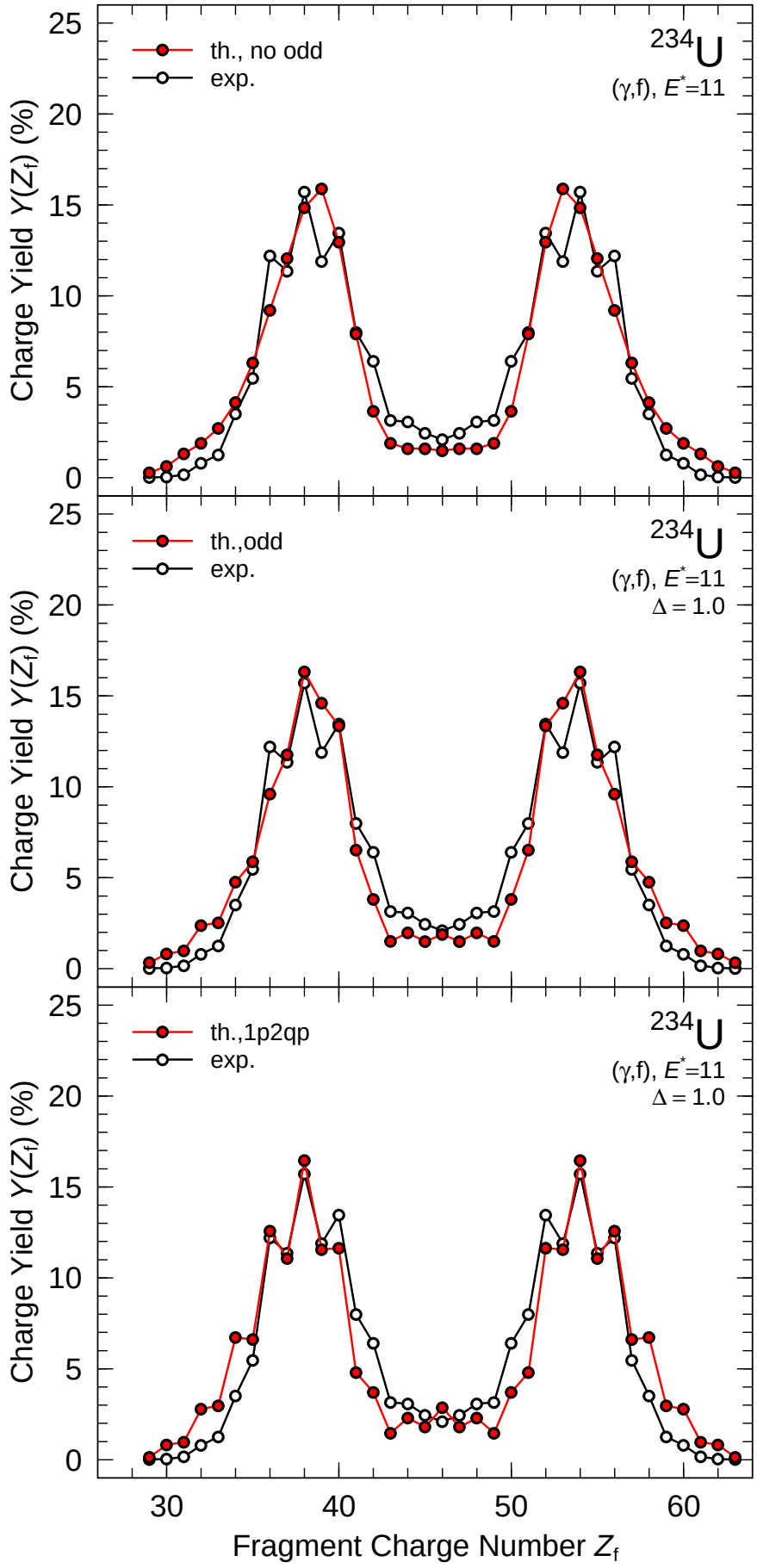

Hexadecapole Deformation ε_4
0.00
0.00
0.00
0.08
0.08
^{272}110
$\lambda_p = 34.80$, $a_p = 0.80$ fm
Single-Proton Energy (MeV)
2
0
−2
−4
−6
−8
128
124
120
110
114
108
106
104
92
86
82
−0.4
−0.2
0.0
0.2
0.4
Spheroidal Deformation ε_2

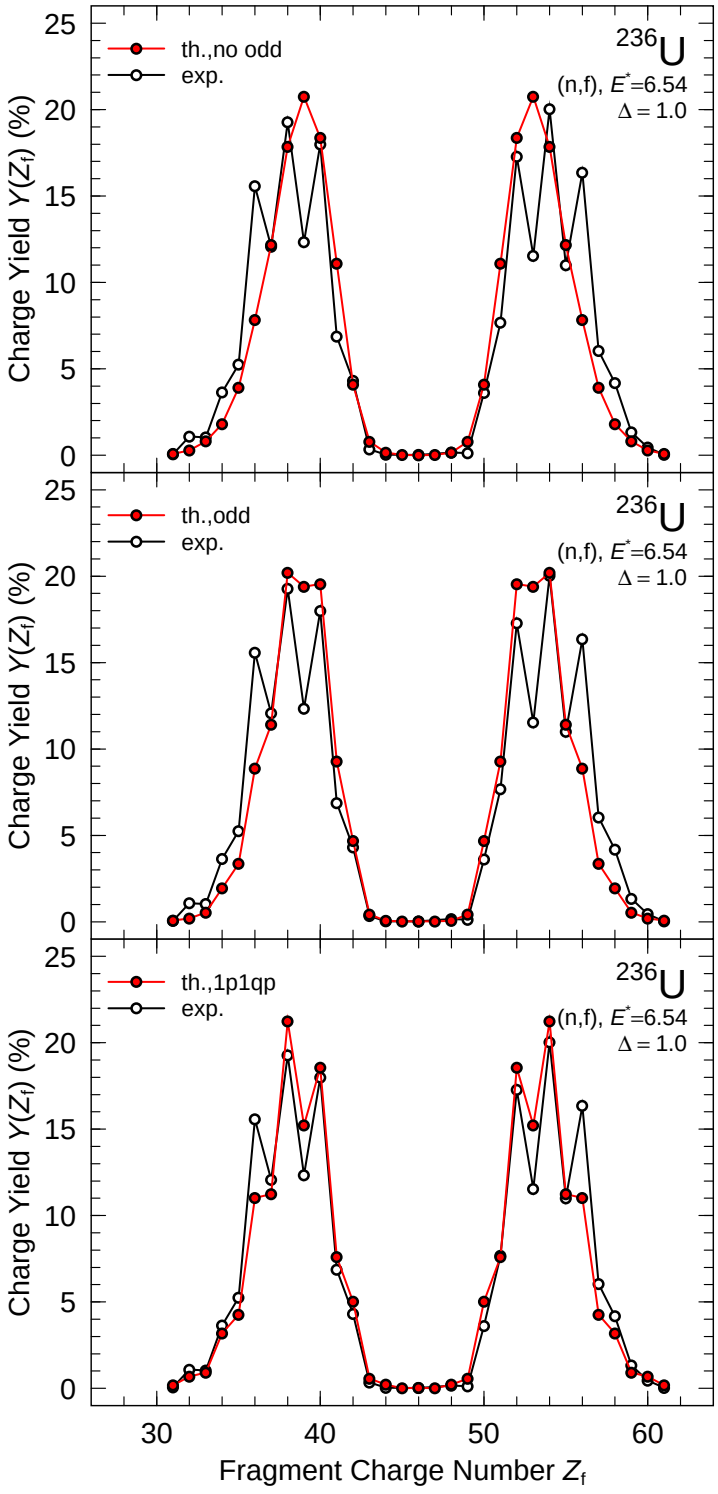

Next Track-Point Candidates
Fragment Charge Z
40
39
38
37
36
I-2
I-1
I
I+1
I+2
Elongation Index

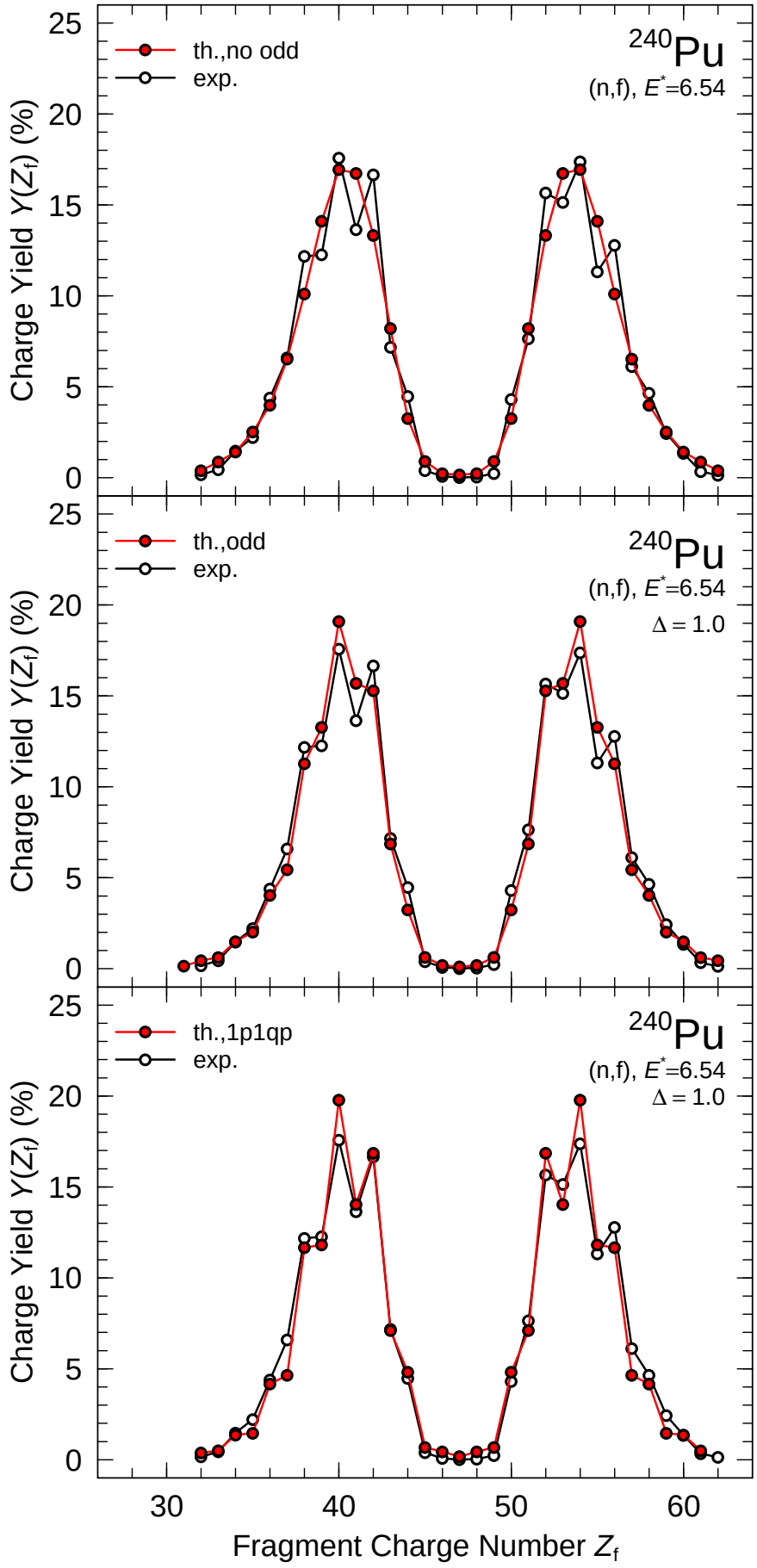

th.,1p1qp
exp.
^{236}U
(n,f), E^*=6.54
Δ = 1.0
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

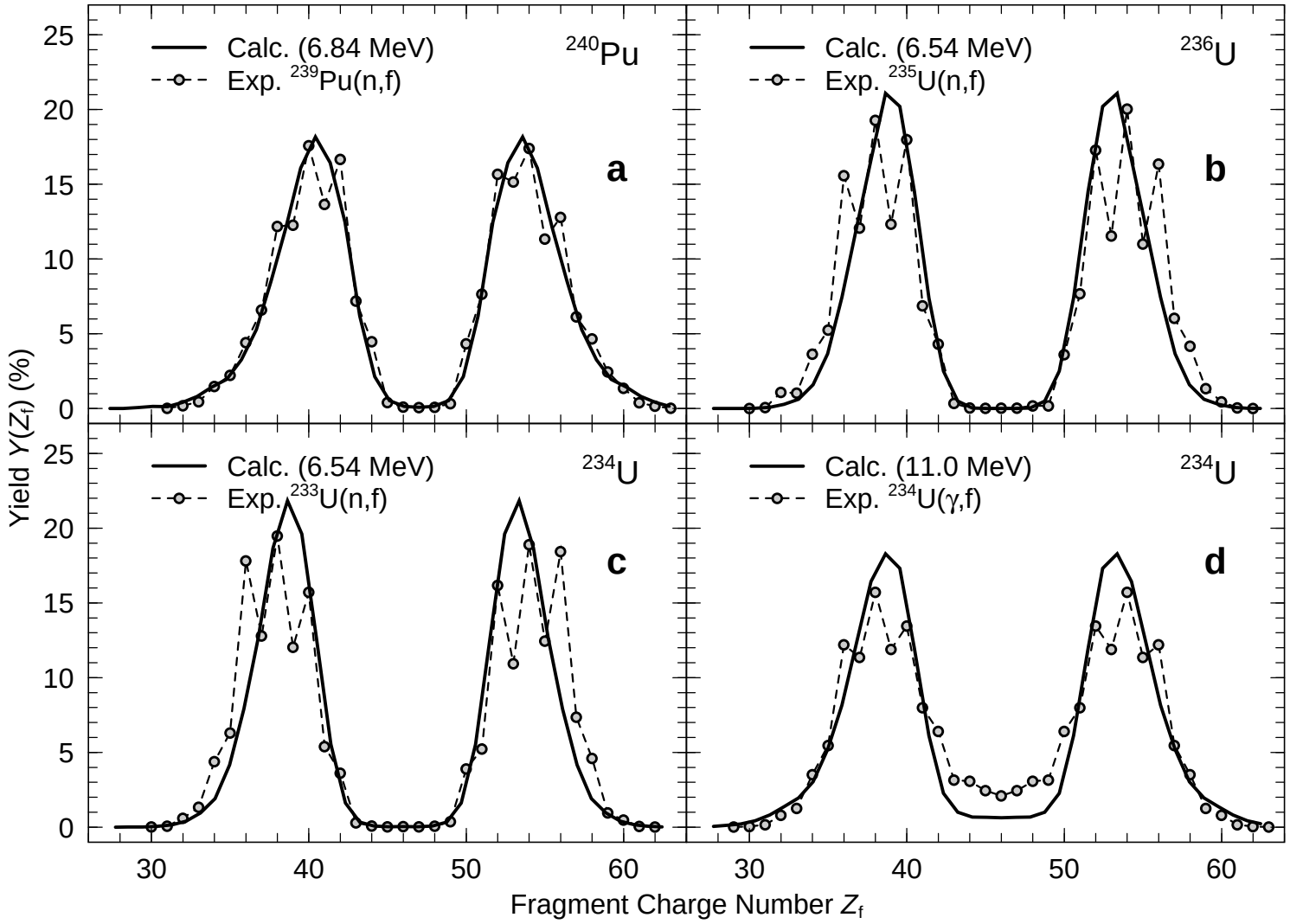

th.,odd
exp.
^{236}U
(n,f), E^*=6.54
Δ = 1.0
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

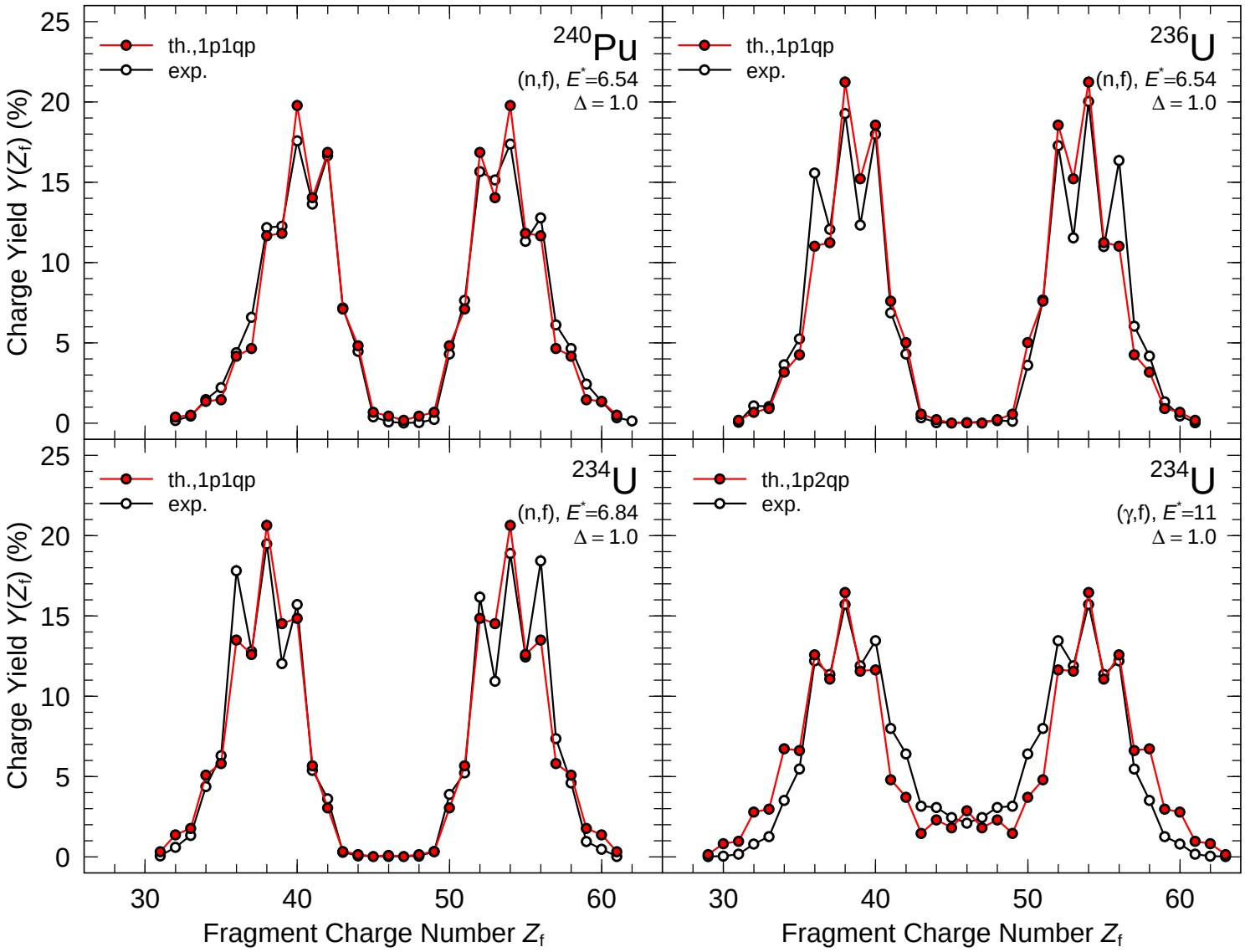

th., no odd
exp.
234U
(n,f), E*=6.84
th.,odd
exp.
234U
(n,f), E*=6.84
Δ = 1.0
th.,1p1qp
exp.
234U
(n,f), E*=6.84
Δ = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60


th., no odd
exp.
234U
(γ,f), E*=11
th.,odd
exp.
234U
(γ,f), E*=11
Δ = 1.0
th.,1p2qp
exp.
234U
(γ,f), E*=11
Δ = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60


th.,no odd
exp.
^{236}U
(n,f), E^*=6.54
Δ = 1.0
th.,odd
exp.
^{236}U
(n,f), E^*=6.54
Δ = 1.0
th.,1p1qp
exp.
^{236}U
(n,f), E^*=6.54
Δ = 1.0
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60


th.,no odd
exp.
240Pu
(n,f), E*=6.54
th.,odd
exp.
240Pu
(n,f), E*=6.54
Δ = 1.0
th.,1p1qp
exp.
240Pu
(n,f), E*=6.54
Δ = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60


Calc. (6.84 MeV)
Exp. 239Pu(n,f)
240Pu
a
Calc. (6.54 MeV)
Exp. 235U(n,f)
236U
b
Calc. (6.54 MeV)
Exp. 233U(n,f)
234U
c
Calc. (11.0 MeV)
Exp. 234U(γ,f)
234U
d
Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60


th.,1p1qp
exp.
^{240}Pu
(n,f), E^*=6.54
Δ = 1.0
th.,1p1qp
exp.
^{236}U
(n,f), E^*=6.54
Δ = 1.0
th.,1p1qp
exp.
^{234}U
(n,f), E^*=6.84
Δ = 1.0
th.,1p2qp
exp.
^{234}U
(γ,f), E^*=11
Δ = 1.0
Charge Yield $Y(Z_f)$ (%)
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60