22nd ASRC International Workshop “Nuclear Fission and Exotic Nuclei”

JAEA, TOKAI, IBARAKI, JAPAN, DECEMBER 3-5, 2014

Fission-fragment yields for nuclei with $A > 170$

Peter Möller

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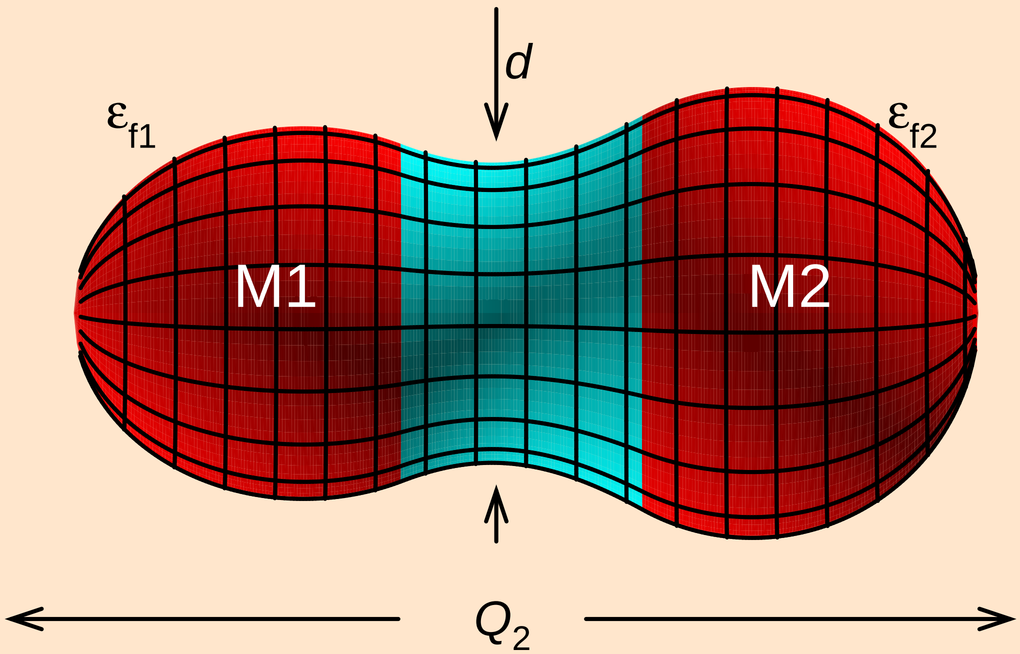
A. J. Sierk (LANL), W. D. Myers, J. Randrup (LBL), M. Mumpower (Notre Dame), H. Sagawa (Aizu), S. Yoshida (Hosei), T. Ichikawa (YITP), A. Iwamoto (JAEA), S. Aberg (Lund), R. Bengtsson (Lund), S. Gupta (IIT, Ropar), and many experimental groups (e. g. K.-L. Kratz (Mainz), H. Schatz (MSU), A. Andreyev (York), K. Nishio (JAEA) . . .).

More details about masses, other projects (beta-decay,fission), 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/

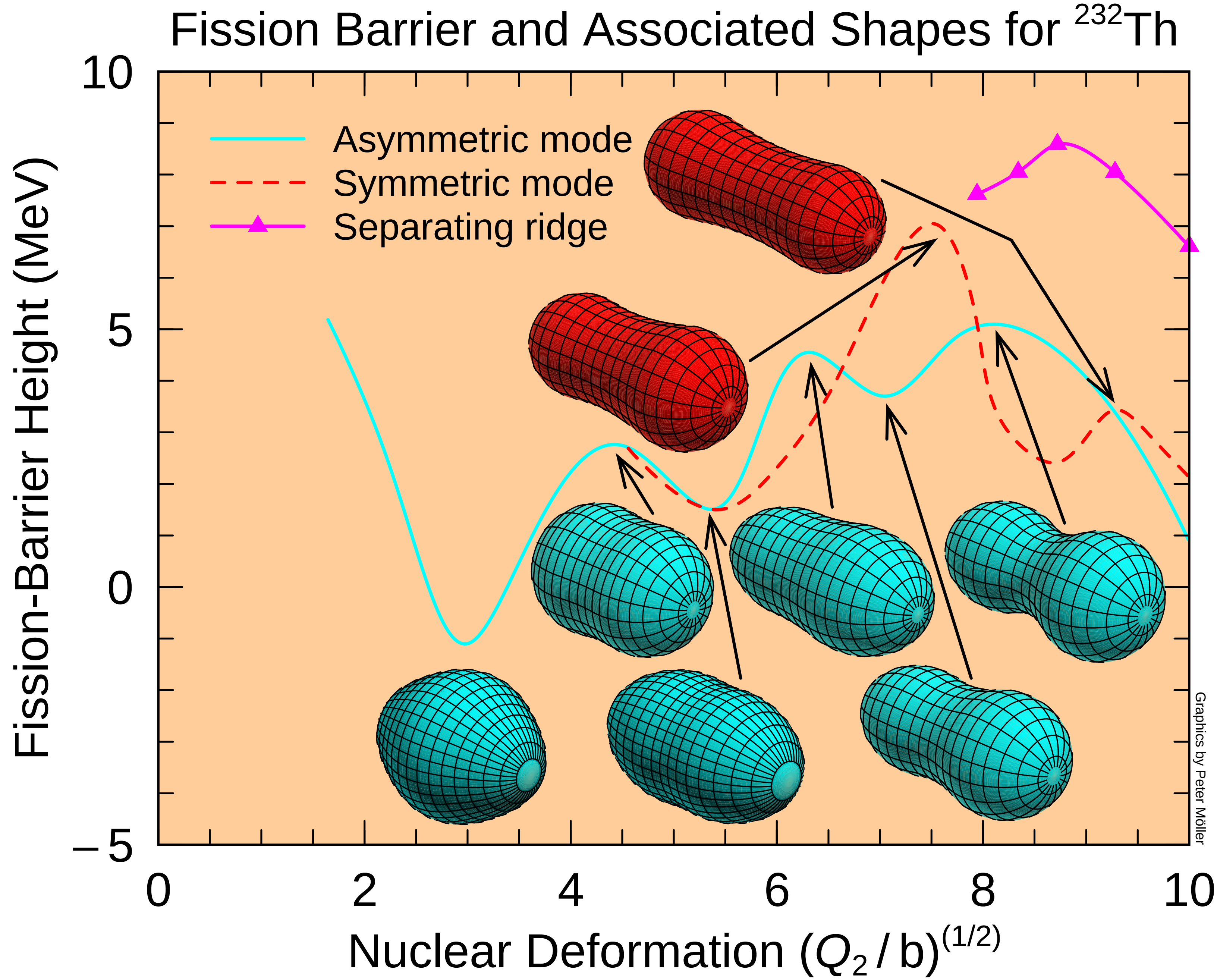
Five Essential Fission Shape Coordinates



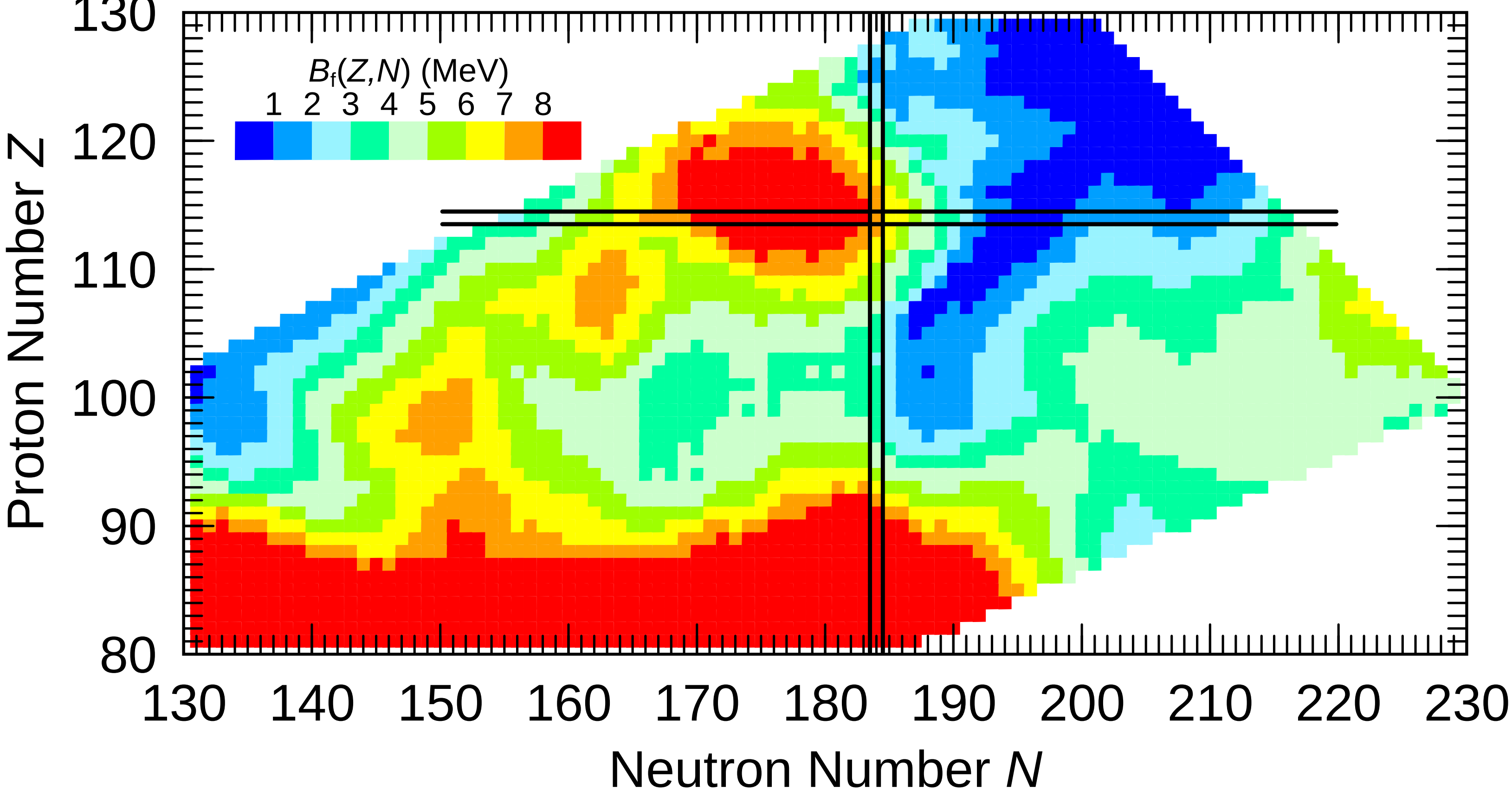
45 Q_2 ~ Elongation (fission direction)
⊗
35 α_g ~ (M1-M2)/(M1+M2) Mass asymmetry
⊗
15 ε_{f1} ~ Left fragment deformation
⊗
15 ε_{f2} ~ Right fragment deformation
⊗
15 d ~ Neck

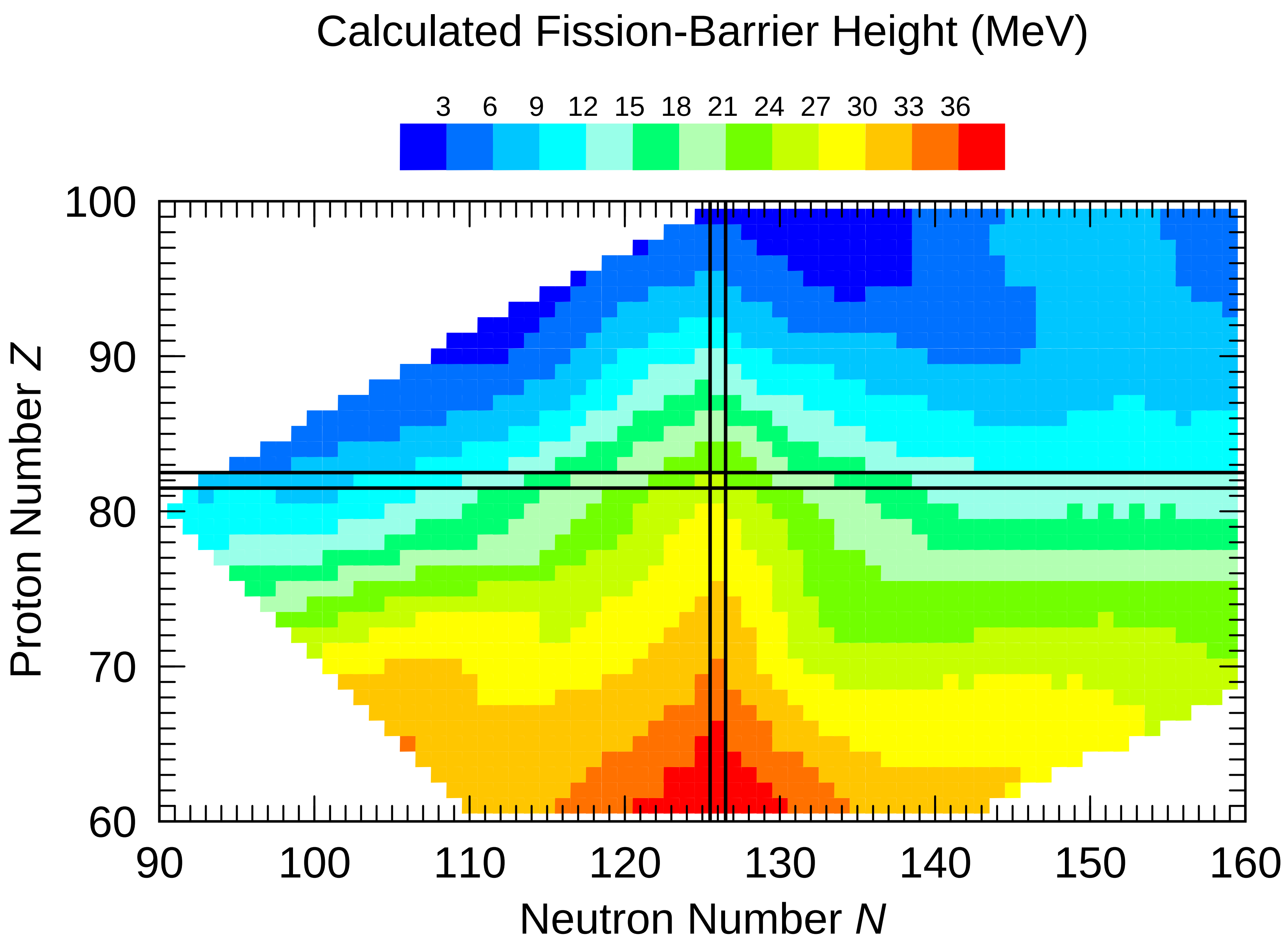
⇒ 5 315 625 grid points – 306 300 unphysical points

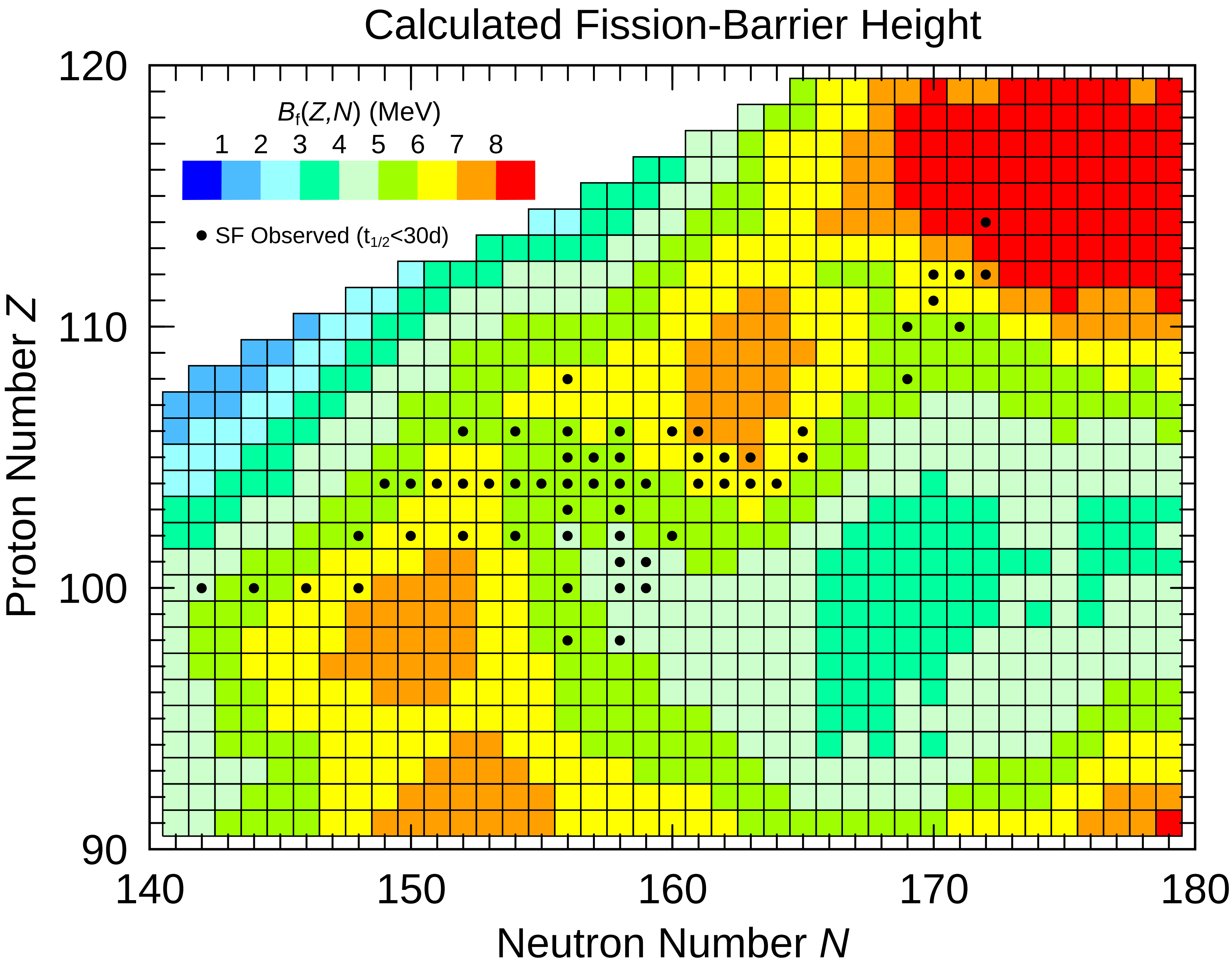
⇒ 5 009 325 physical grid points


Fission Barrier and Associated Shapes for 232Th
Asymmetric mode
Symmetric mode
Separating ridge
Fission-Barrier Height (MeV)
Nuclear Deformation (Q2 / b)(1/2)
10
5
0
−5
0
2
4
6
8
10
Graphics by Peter Möller

Calculated Fission-Barrier Height




Calculated Fission-Barrier Height (MeV)
3
6
9
12
15
18
21
24
27
30
33
36
100
90
80
70
60
Proton Number Z
90
100
110
120
130
140
150
160
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
90
100
110
120
Neutron Number N
140
150
160
170
180

EPJ Web of Conferences **66**, 02046 (2014)
DOI: 10.1051/epjconf/20146602046

Exploring the stability of super heavy elements: First Measurement of the Fission Barrier of ^{254}No

G. Henning[1,2a], A. Lopez-Martens[1,b] , T.L. Khoo[2], D. Seweryniak[2],M. Alcorta[2], M. Asai[3], B. B. Back[2], P. Bertone[2], D. Boilley[4], M. P. Carpenter[2], C. J. Chiara[2,5], P. Chowdhury[6], B. Gall[7], P. T. Greenlees[8], G. Gurdal[6], K. Hauschild[1], A. Heinz[9], C. R. Hoffman[2], R. V. F. Janssens[2], A. V. Karpov[10], B. P. Kay[2], F. G. Kondev[2], S. Lakshmi[6], T. Lauristen[2], C. J. Lister[6], E. A. McCutchan[2], C. Nair[2], J. Piot[7c], D. Potterveld[2], P. Reiter[11], N. Rowley[12], A. M. Rogers[2], and S. Zhu[2]

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[2] *Argonne National Laboratory, USA*
[3] *Japan Atomic Energy Agency, Japan*
[4] *GANIL, CEA and IN2P3/CNRS and Normandie Université, France*
[5] *University of Maryland, USA*
[6] *Univeristy of Massachusetts Lowell, USA*
[7] *IPHC, IN2P3/CNRS and Université Louis Pasteur, France*
[8] *Unviersity of Jyväskylä, Finland*
[9] *Chalmers Tekniska Hogskola, Sweden*
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Abstract. The gamma-ray multiplicity and total energy emitted by the heavy nucleus ^{254}No have been measured at 2 different beam energies. From these measurements, the initial distributions of spin I and excitation energy E^* of ^{254}No were constructed. The distributions display a saturation in excitation energy, which allows a direct determination of the fission barrier. ^{254}No is the heaviest shell-stabilized nucleus with a measured fission barrier.

1 Introduction

The nucleus of interest ^{254}No is situated at the very top of the chart of nuclides, in the region of the very heavy and super heavy elements. These nuclei are very special in that they are characterized by a decreasing and, for the heavier ones, a vanishing liquid drop fission barrier.

The reason why ^{254}No does not fission with a very short lifetime [1] or why one has recently been able to synthesize and observe element 118 [2] is because of quantum-mechanical shell effects. Indeed, it is the gaps in the single-particle spectrum, which give additional binding to the nucleus and lower the ground state with respect to the liquid drop energy, thereby creating a barrier against fission.

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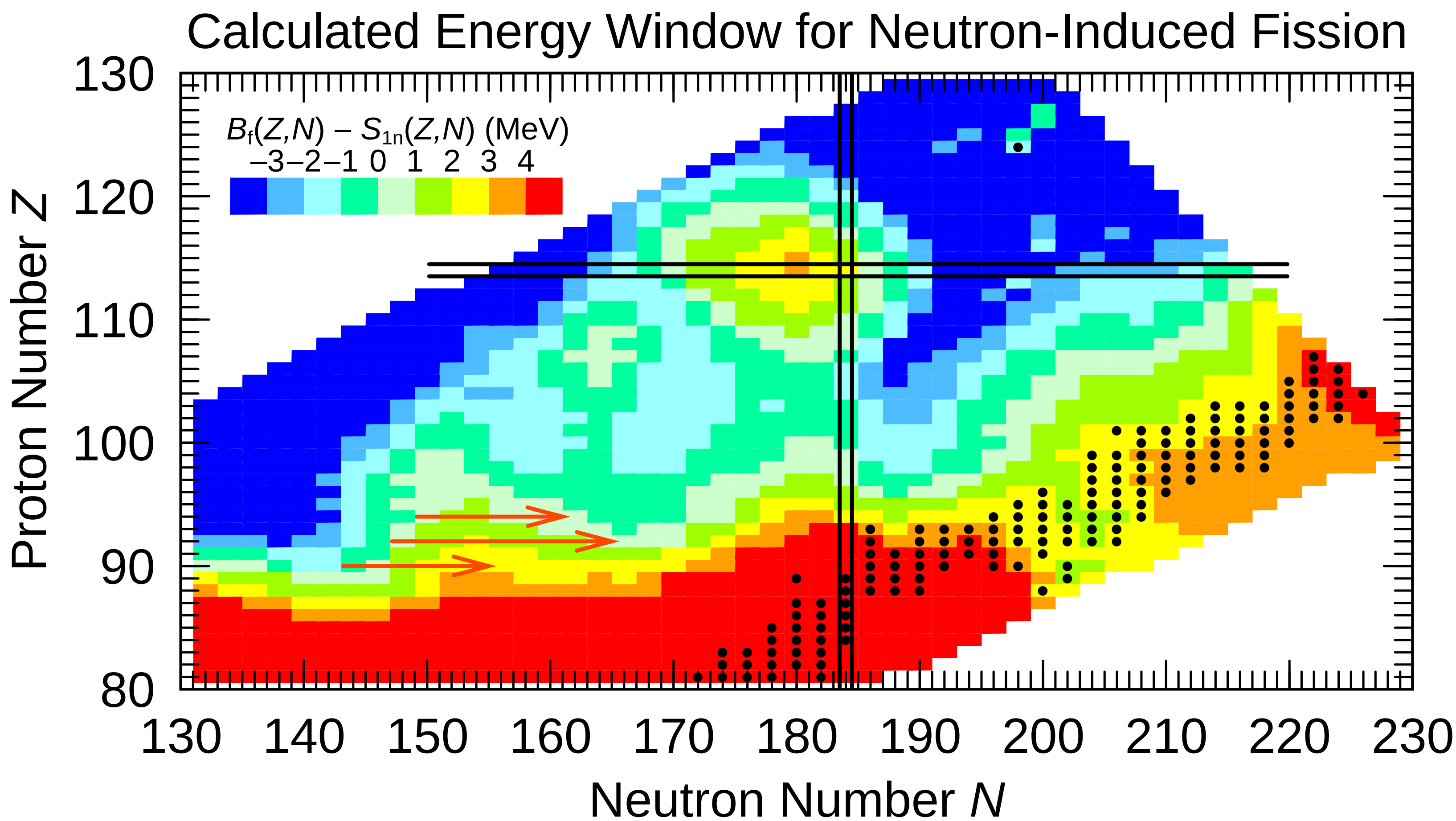
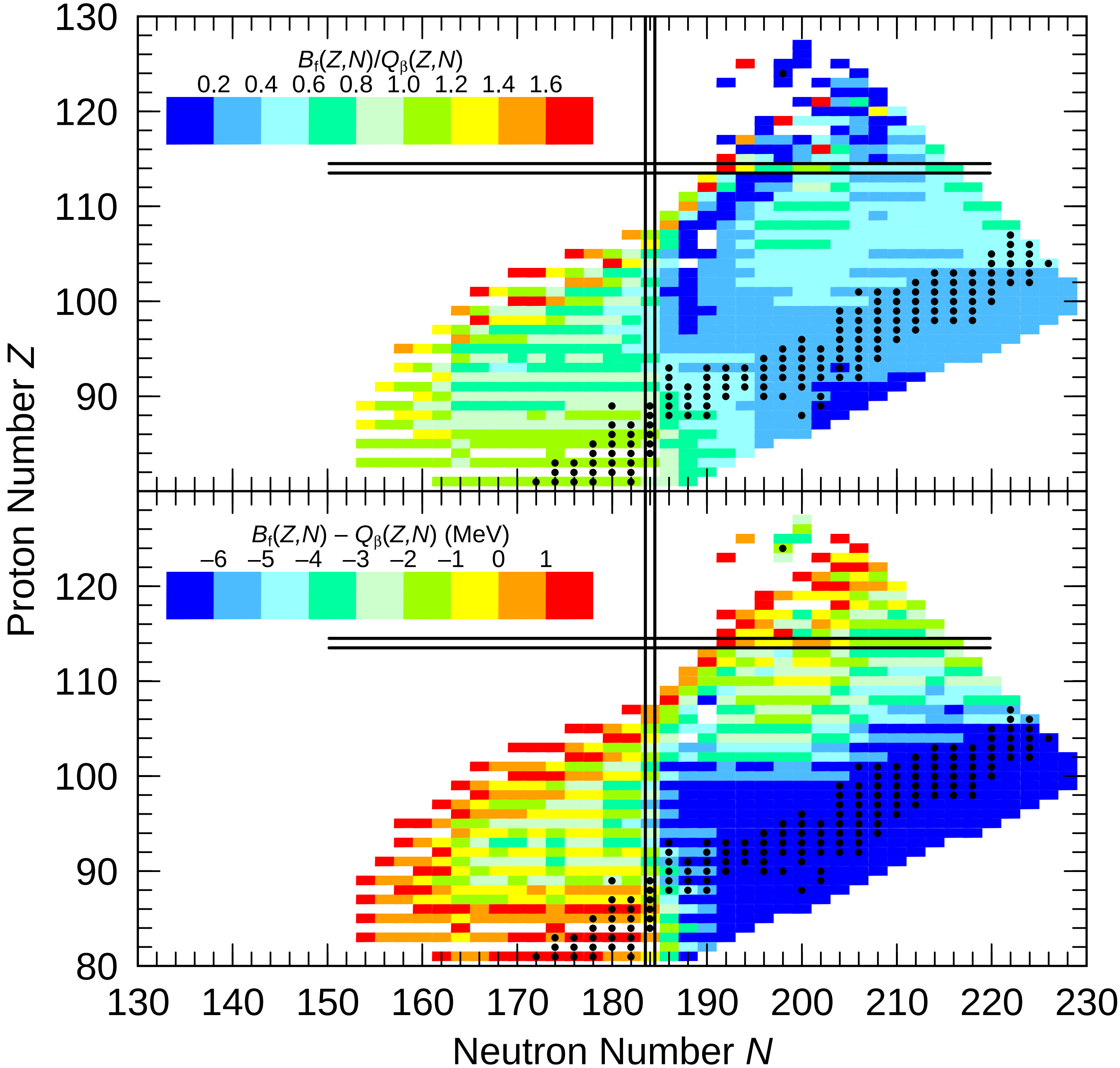
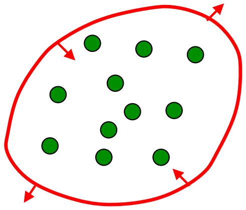
[c] Current address: GANIL

Article available at http://www.epj-conferences.org or http://dx.doi.org/10.1051/epjconf/20146602046


Calculated Energy Window for Neutron-Induced Fission
$B_f(Z,N) - S_{1n}(Z,N)$ (MeV)
−3 −2 −1 0 1 2 3 4
Proton Number Z
Neutron Number N
130
120
110
100
90
80
130 140 150 160 170 180 190 200 210 220 230



Bf(Z,N)/Qβ(Z,N)
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6
Bf(Z,N) − Qβ(Z,N) (MeV)
−6 −5 −4 −3 −2 −1 0 1
130
120
110
100
90
80
Proton Number Z
130 140 150 160 170 180 190 200 210 220 230
Neutron Number N



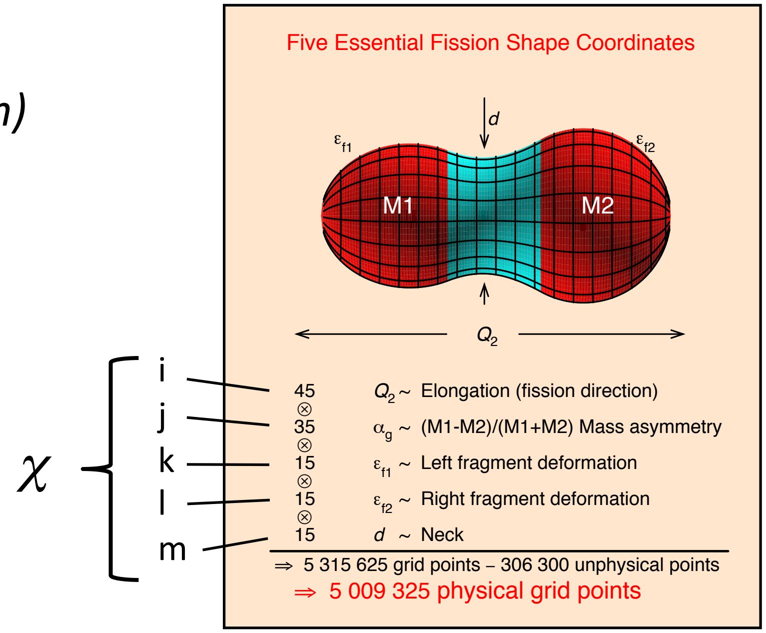
Brownian shape motion

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: $a_A = A/(8\ \mathrm{MeV})$

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



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

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

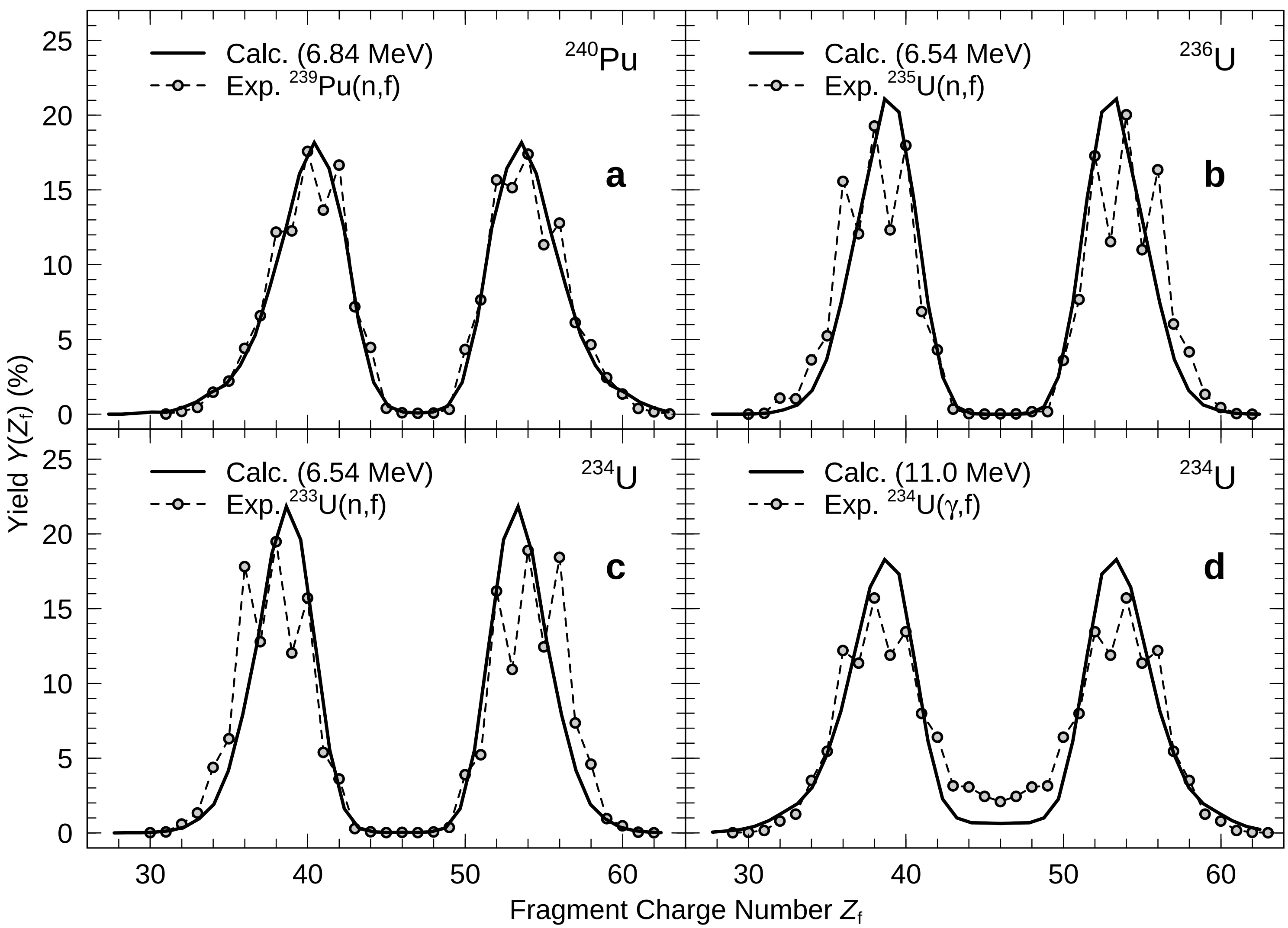
Metropolis walk:

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

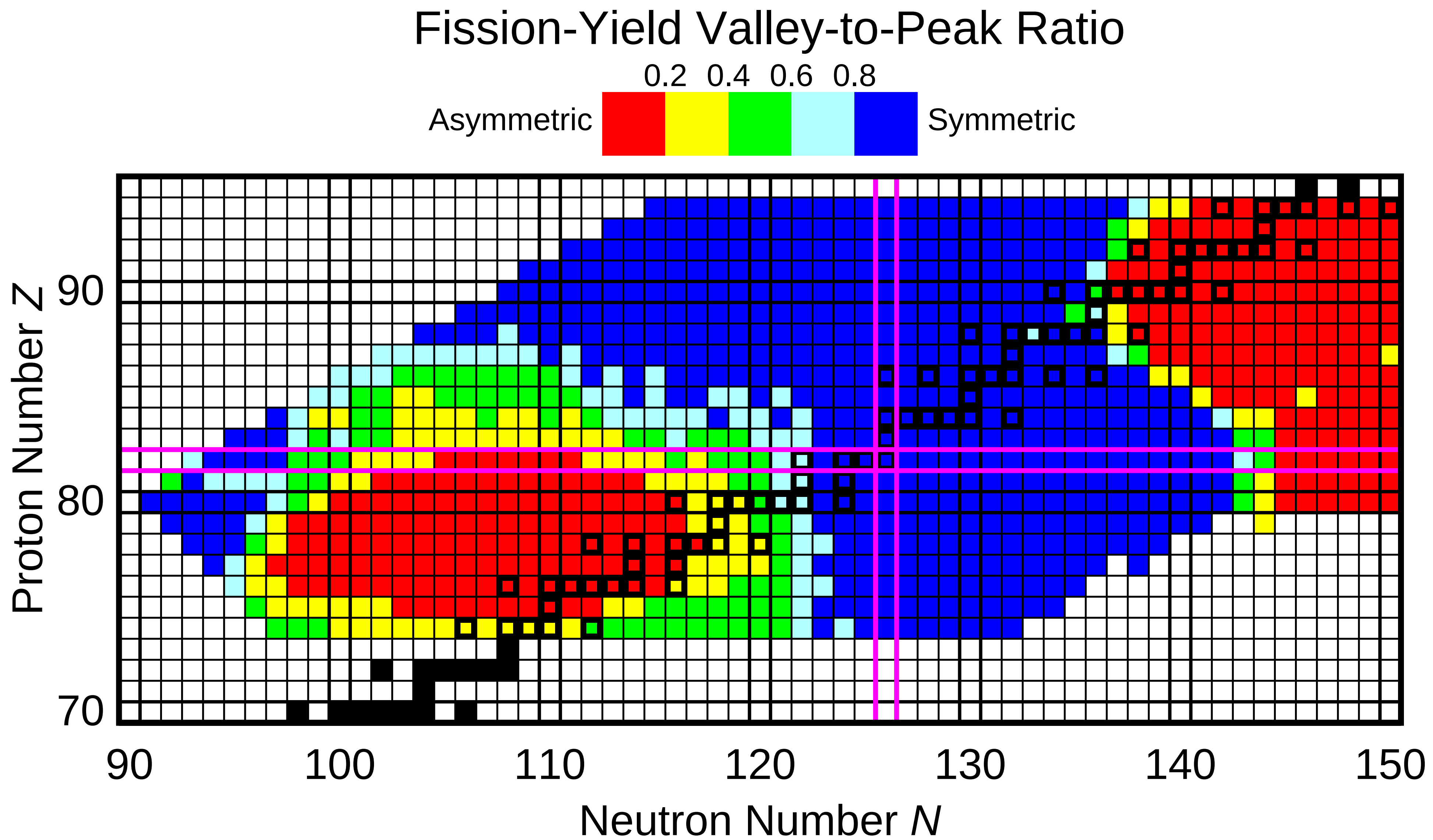
Change shape: $\chi \rightarrow \chi'$?

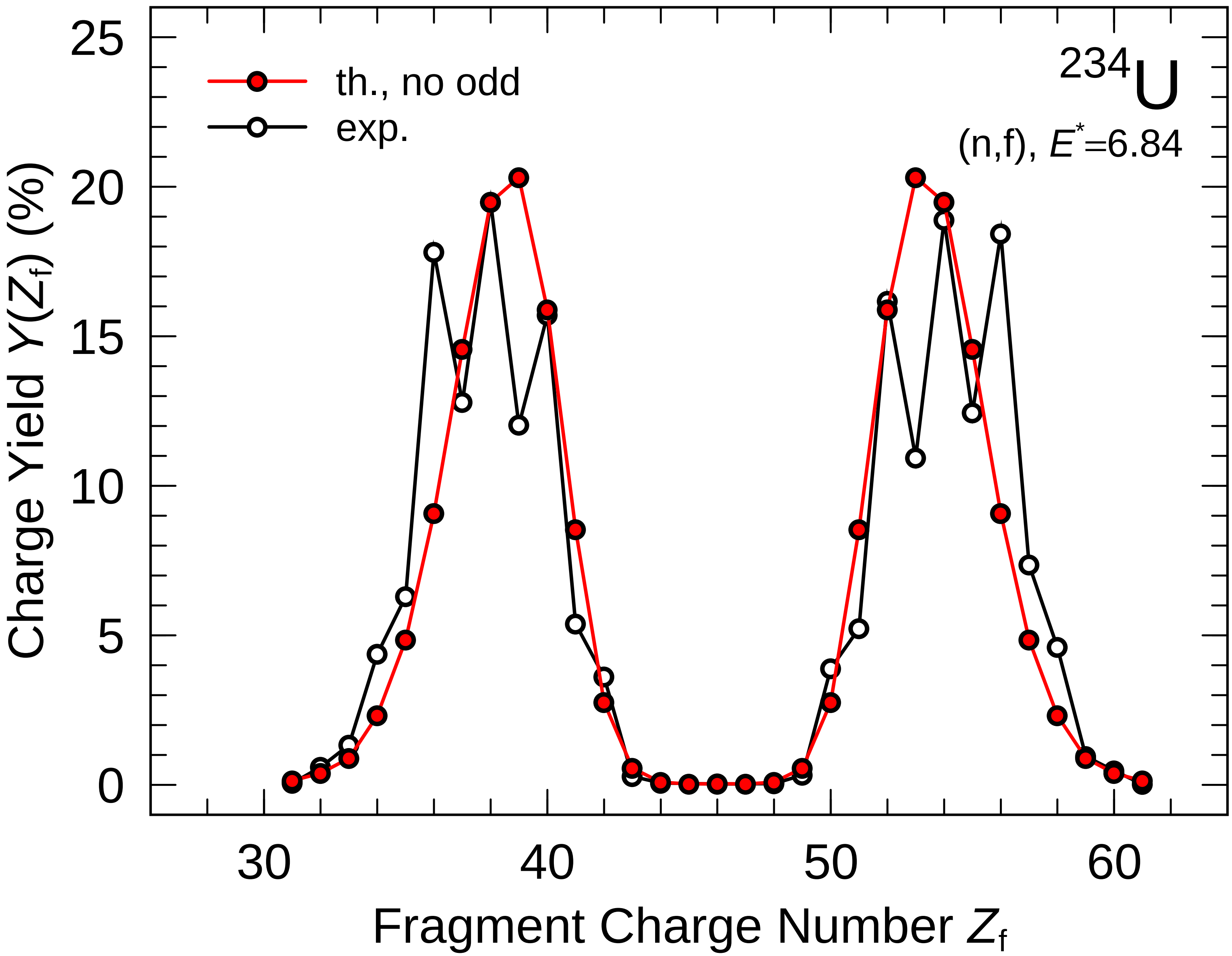
- $V(\chi') < V(\chi)$: *move with* $P = 1$
- $V(\chi') > V(\chi)$: *move with* $P = \exp(-\Delta V/T)$

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



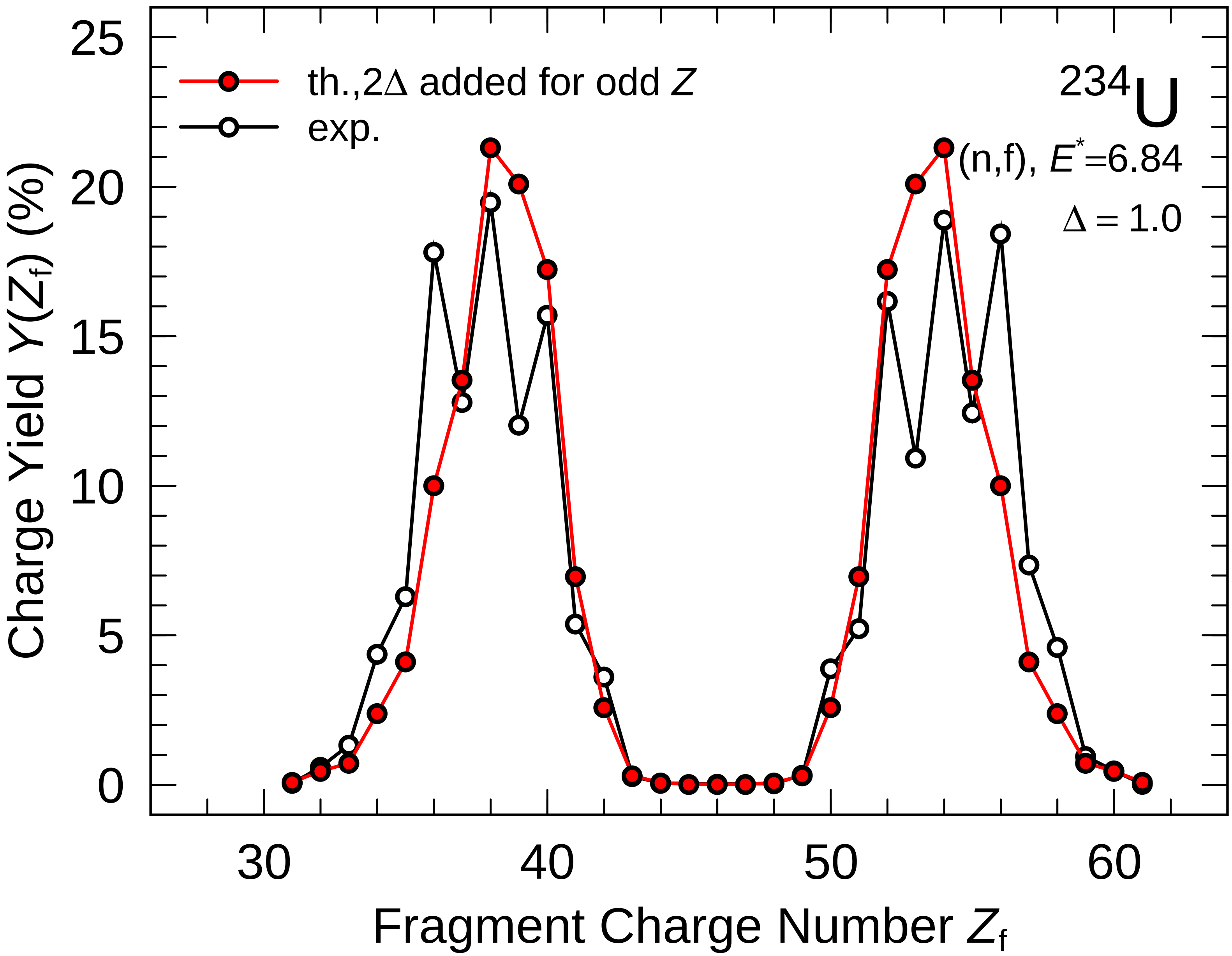
Calc. (6.84 MeV)
Exp. 239Pu(n,f)
240Pu
a
Calc. (6.54 MeV)
Exp. 235U(n,f)
236U
b
Calc. (6.54 MeV)
Exp. 233U(n,f)
234U
c
Calc. (11.0 MeV)
Exp. 234U(γ,f)
234U
d
Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60


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

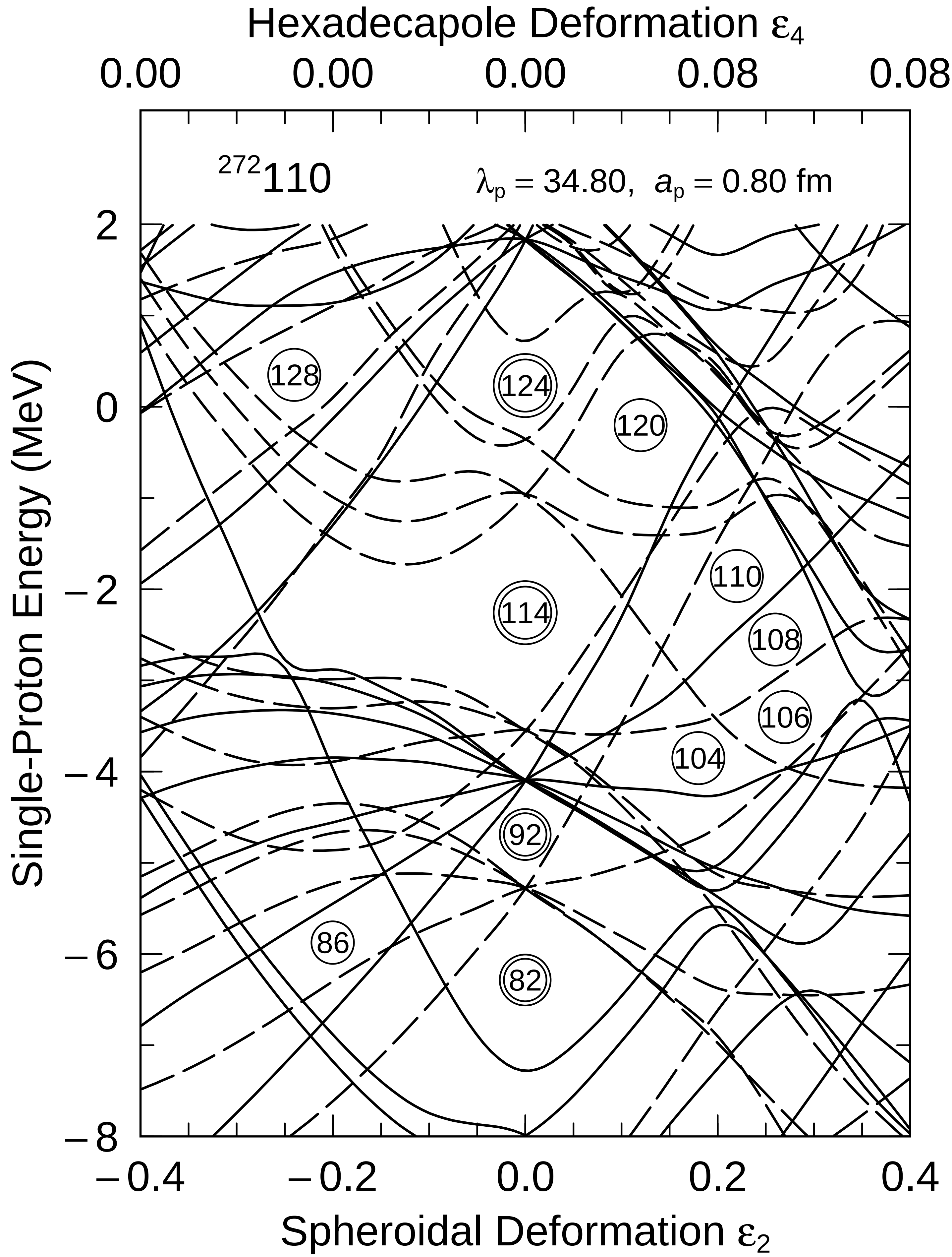


th., no odd
exp.
234U
(n,f), E*=6.84
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

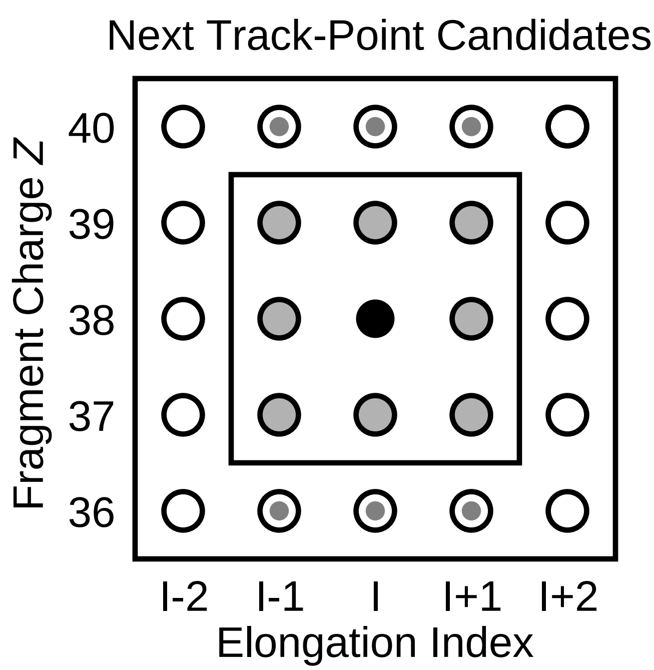
```
READ(LU,'(2f10.3)') r,rw

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
```

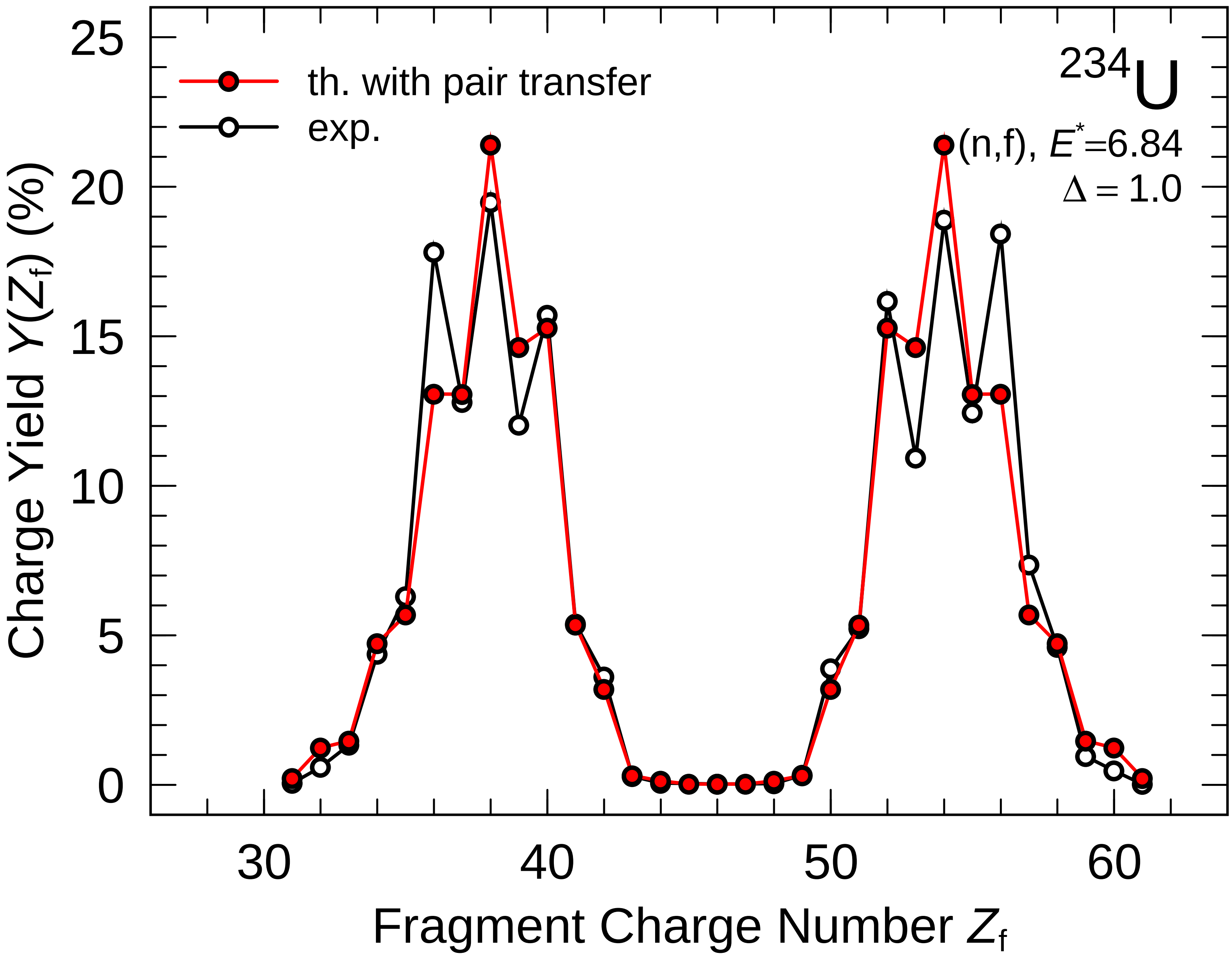


th.,2Δ added for odd Z
exp.
234U
(n,f), E*=6.84
Δ = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

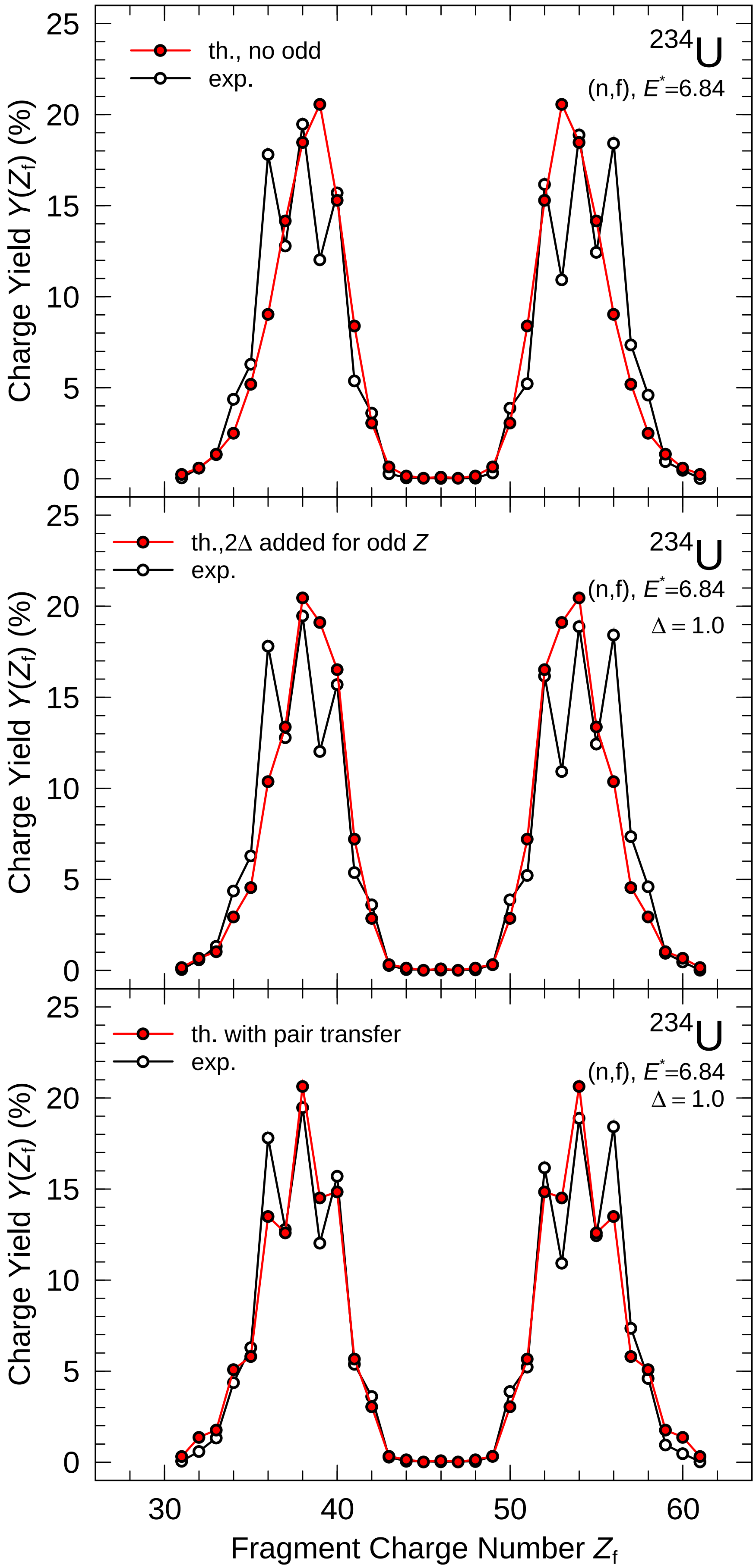


Hexadecapole Deformation ε_4
0.00
0.00
0.00
0.08
0.08
$^{272}110$
$\lambda_p = 34.80$, $a_p = 0.80$ fm
128
124
120
114
110
108
106
104
92
86
82
2
0
−2
−4
−6
−8
Single-Proton Energy (MeV)
−0.4
−0.2
0.0
0.2
0.4
Spheroidal Deformation ε_2

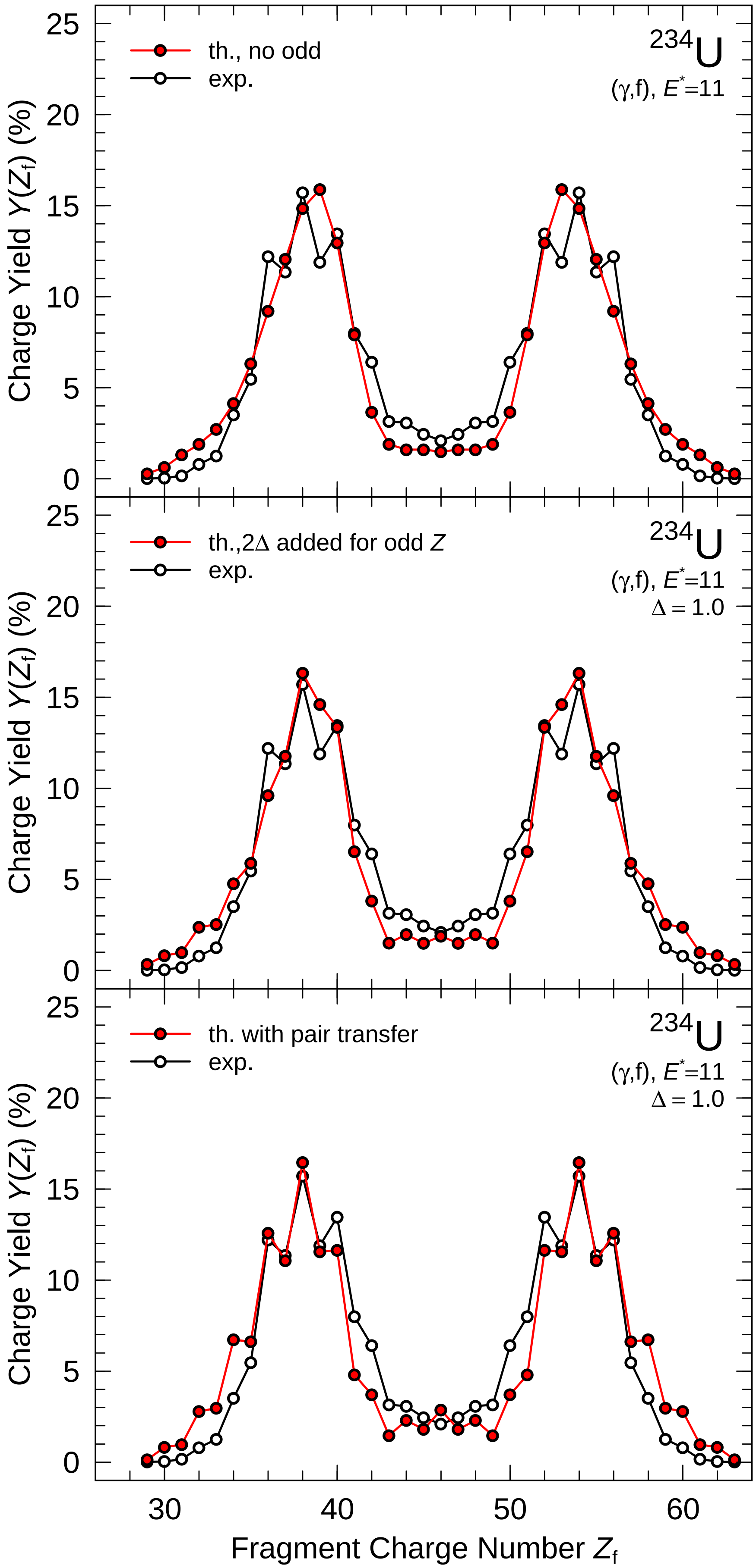

Next Track-Point Candidates
Fragment Charge Z
40
39
38
37
36
I-2
I-1
I
I+1
I+2
Elongation Index



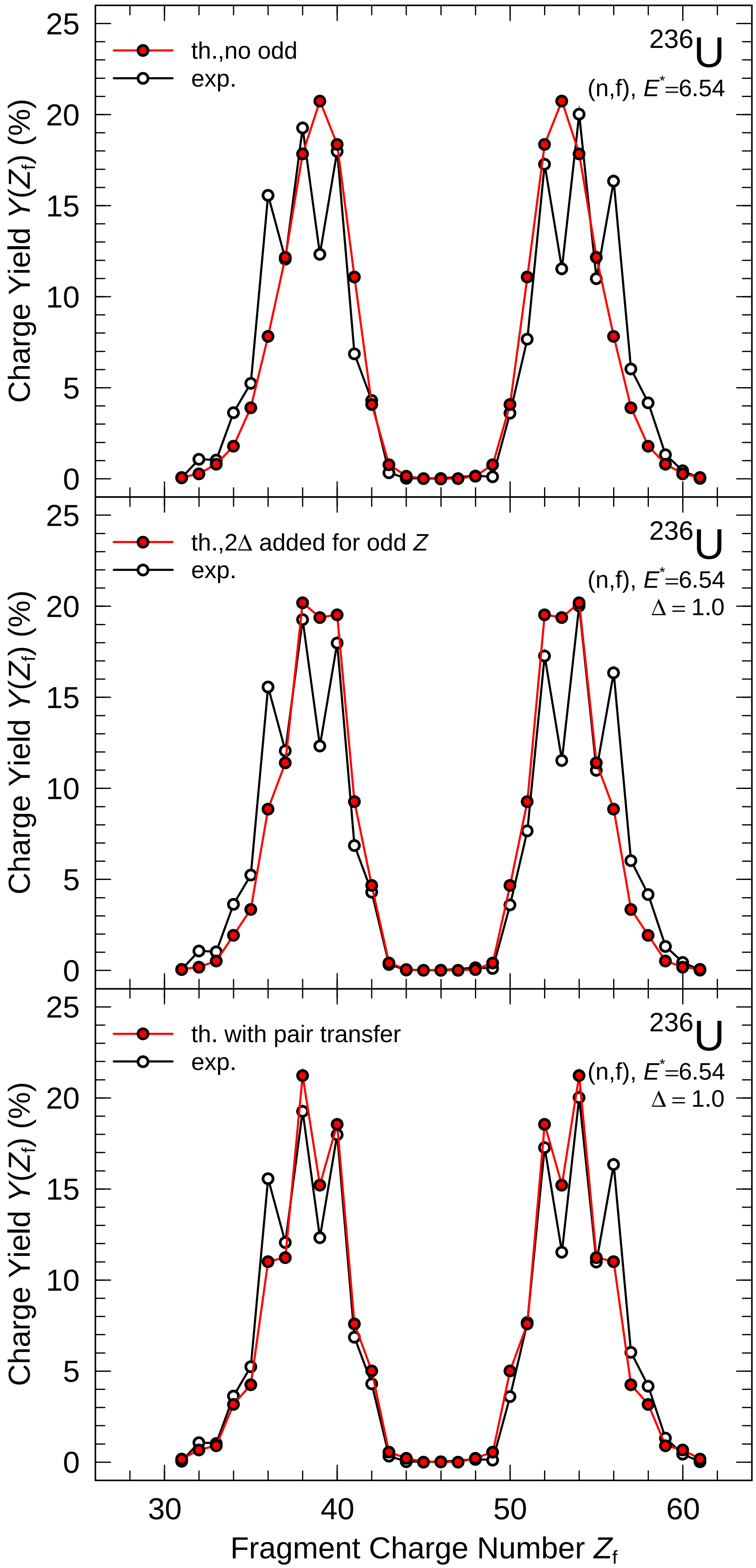
th. with pair transfer
exp.
234U
(n,f), E*=6.84
Δ = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

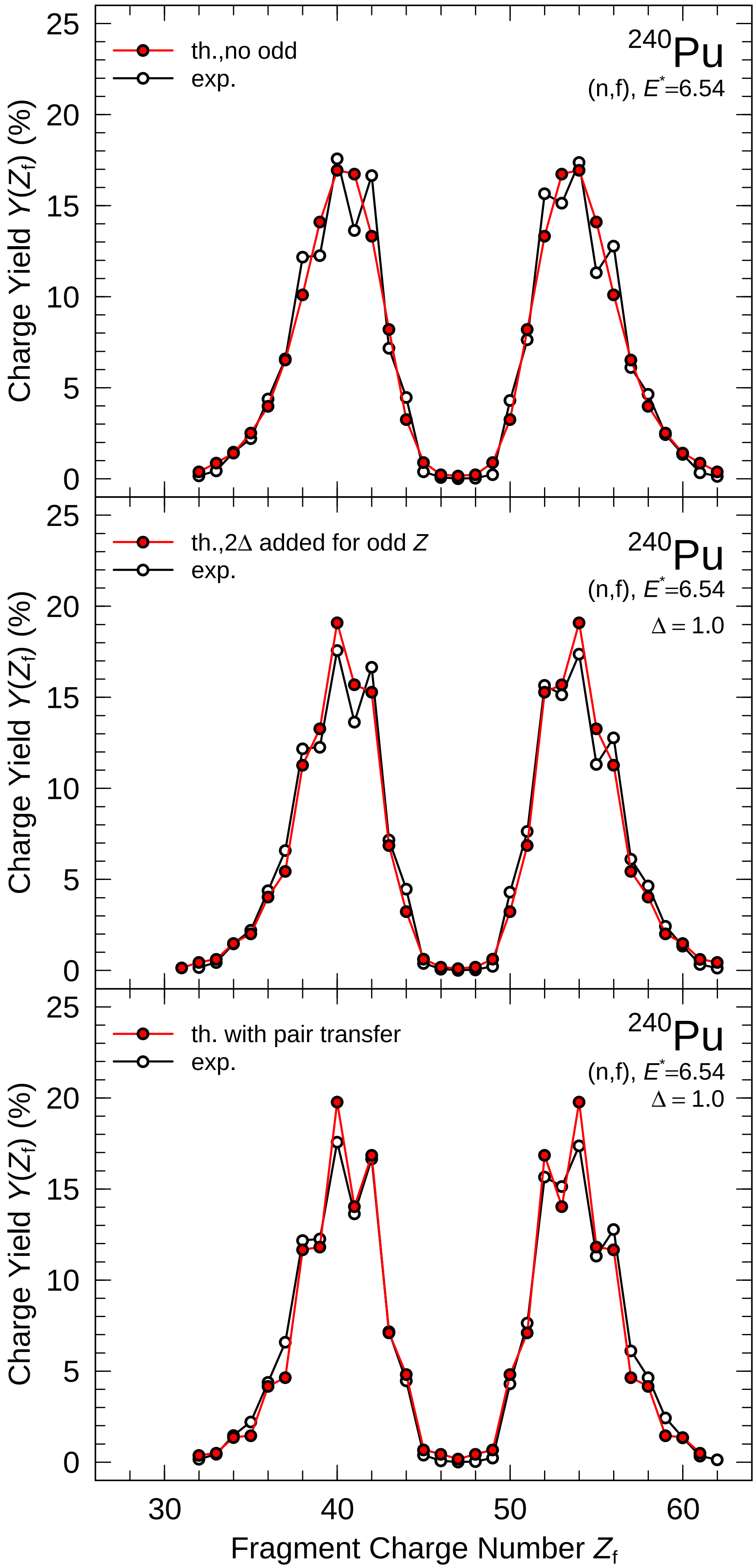


th., no odd
exp.
^{234}U
(n,f), E^*=6.84
th.,2Δ added for odd Z
exp.
^{234}U
(n,f), E^*=6.84
Δ = 1.0
th. with pair transfer
exp.
^{234}U
(n,f), E^*=6.84
Δ = 1.0
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f

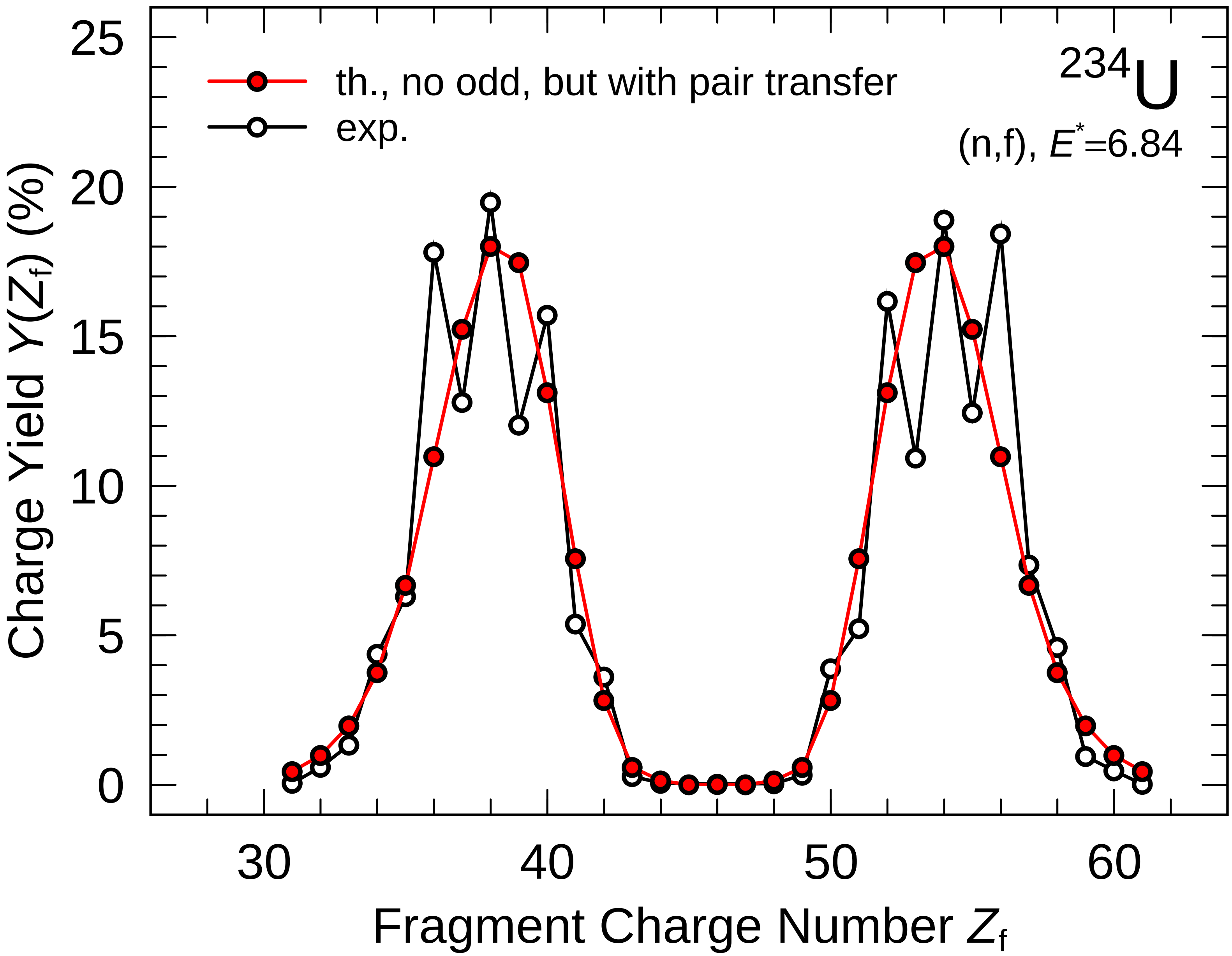


th., no odd
exp.
234U
(γ,f), E*=11
th.,2Δ added for odd Z
exp.
234U
(γ,f), E*=11
Δ = 1.0
th. with pair transfer
exp.
234U
(γ,f), E*=11
Δ = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf

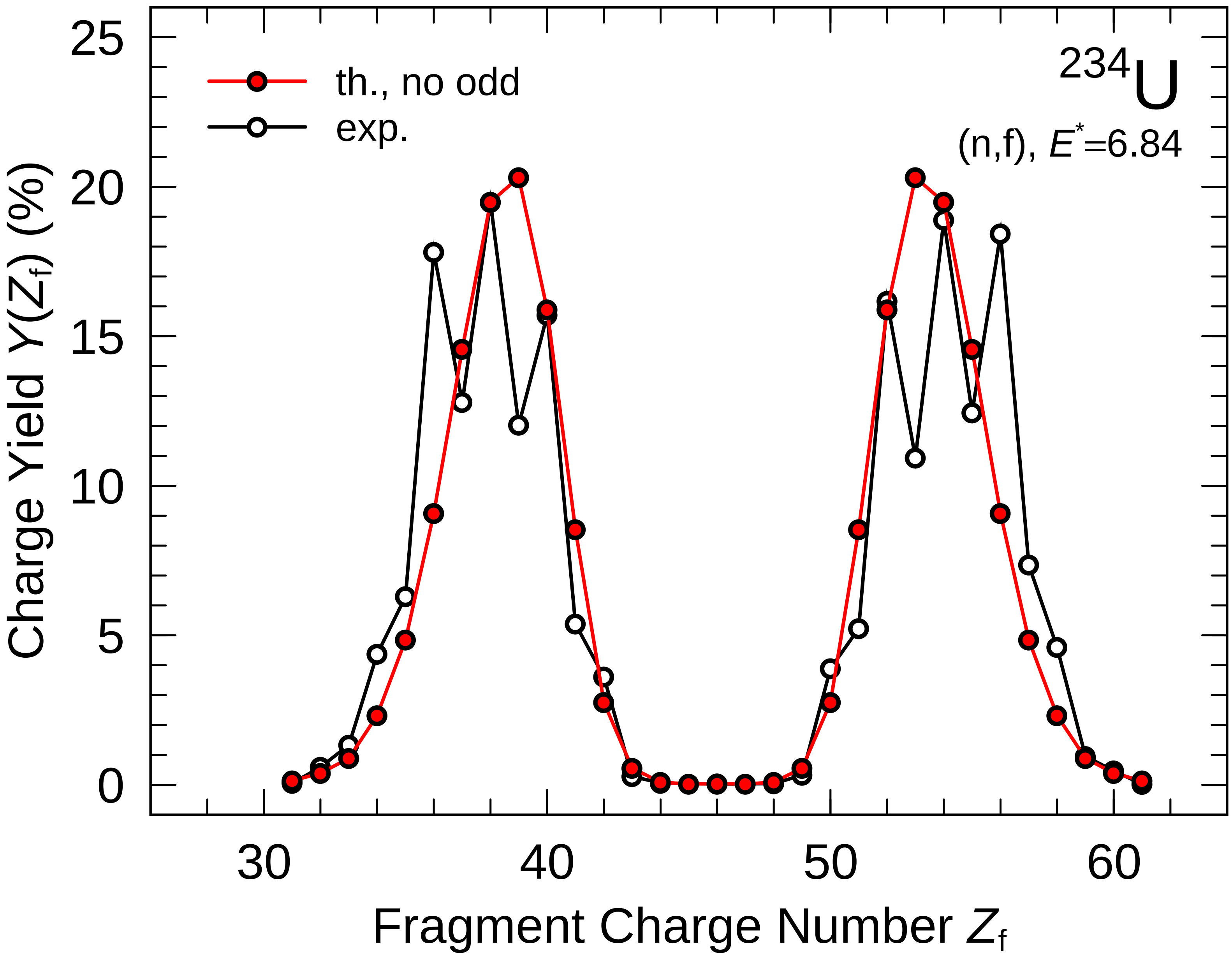

th.,no odd
exp.
236U
(n,f), E*=6.54
th.,2Δ added for odd Z
exp.
236U
(n,f), E*=6.54
Δ = 1.0
th. with pair transfer
exp.
236U
(n,f), E*=6.54
Δ = 1.0
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60



th.,no odd
exp.
^{240}Pu
(n,f), E^*=6.54
th.,2Δ added for odd Z
exp.
^{240}Pu
(n,f), E^*=6.54
Δ = 1.0
th. with pair transfer
exp.
^{240}Pu
(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, but with pair transfer
exp.
234U
(n,f), E*=6.84
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60



th., no odd
exp.
^{234}U
(n,f), E^*=6.84
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

Modeling in BSM of $Y(Z_1, N_1, Z - Z_1, N - N_1)$

We need total potential energy versus fragment proton and neutron numbers. Shell correction is actually straightforward.

Total shell correction:

$$ESH_{Z+N}(Z_1, N_1, Z - Z_1, N - N_1)$$

"Field" asymmetry $\alpha_{\rm g}$ → Asymmetry in N and Z! This means 2 asymmetry coordinates rather than a single "field" asymmetry. How?

Calculate neutron shell correction for grid of $\alpha_{\rm g}$ corresponding to integer N values. Save the *neutron* shell corrections $ESH_N(N_1, N - N_1)$.

Calculate proton shell correction for grid of $\alpha_{\rm g}$ corresponding to integer Z values. Save the *proton* shell corrections $ESH_Z(Z_1, Z - Z_1)$.

$$ESH_{Z+N}(Z_1, N_1, Z - Z_1, N - N_1) = ESH_Z(Z_1, Z - Z_1) + ESH_N(N_1, N - N_1)$$

Modeling in BSM of $Y(Z_1, N_1, Z - Z_1, N - N_1)$

We need total potential energy versus fragment proton and neutron numbers. Now what about the

Macroscopic energy:

$EMAC_{Z+N}(Z_1, N_1, Z - Z_1, N - N_1)$

Start by calculating $EMAC_{\text{comp}}$ for the compound nucleus for a grid in α_{g} corresponding to integer Z_1 and $Z - Z_1$.

The neutron numbers in the fragments corresponding to the α_{g} yielding these integer Z_1 are not integers.

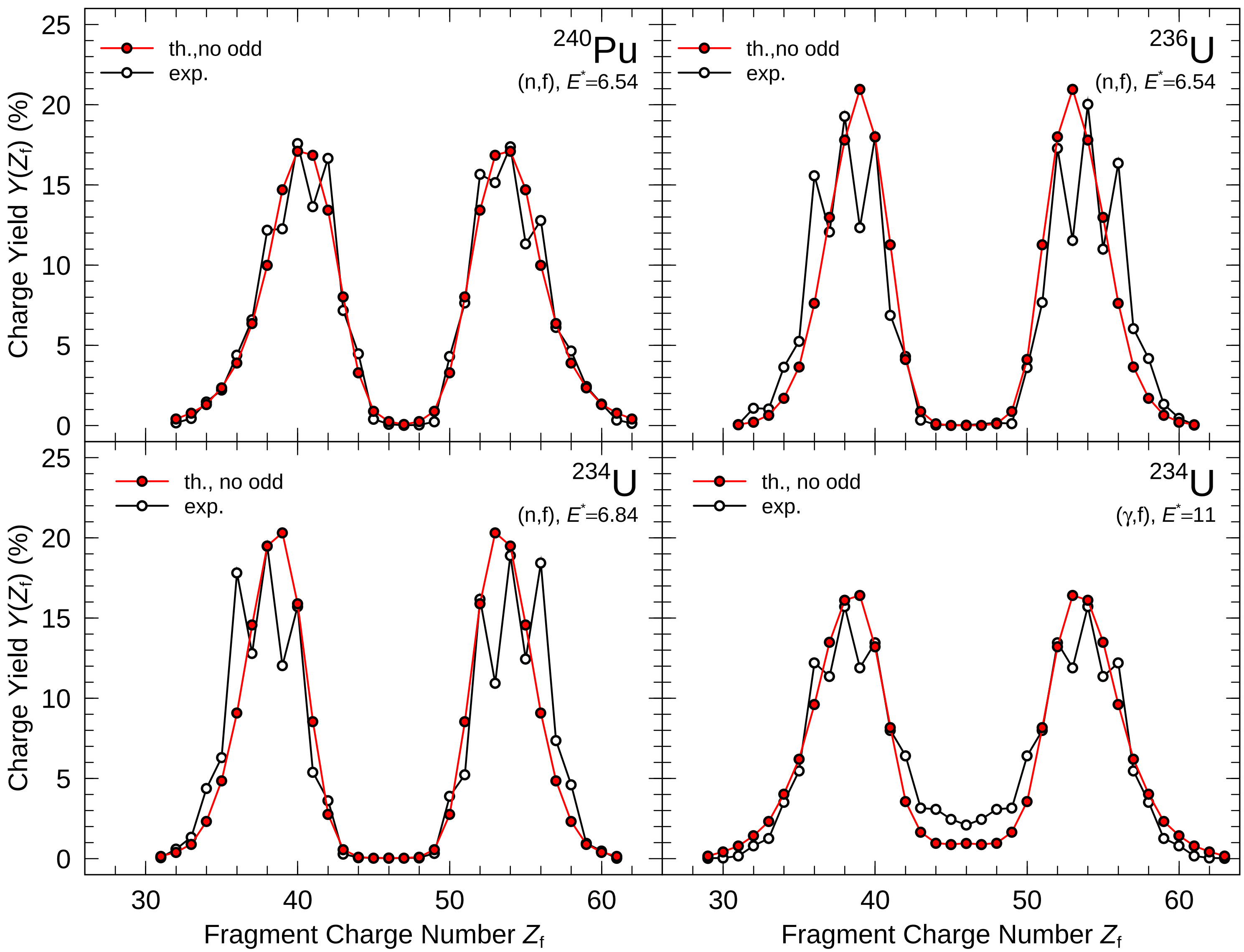
Now fix Z_1 and calculate the macroscopic energy for this (fixed) Z_1 but for different integer N_ν as the sum

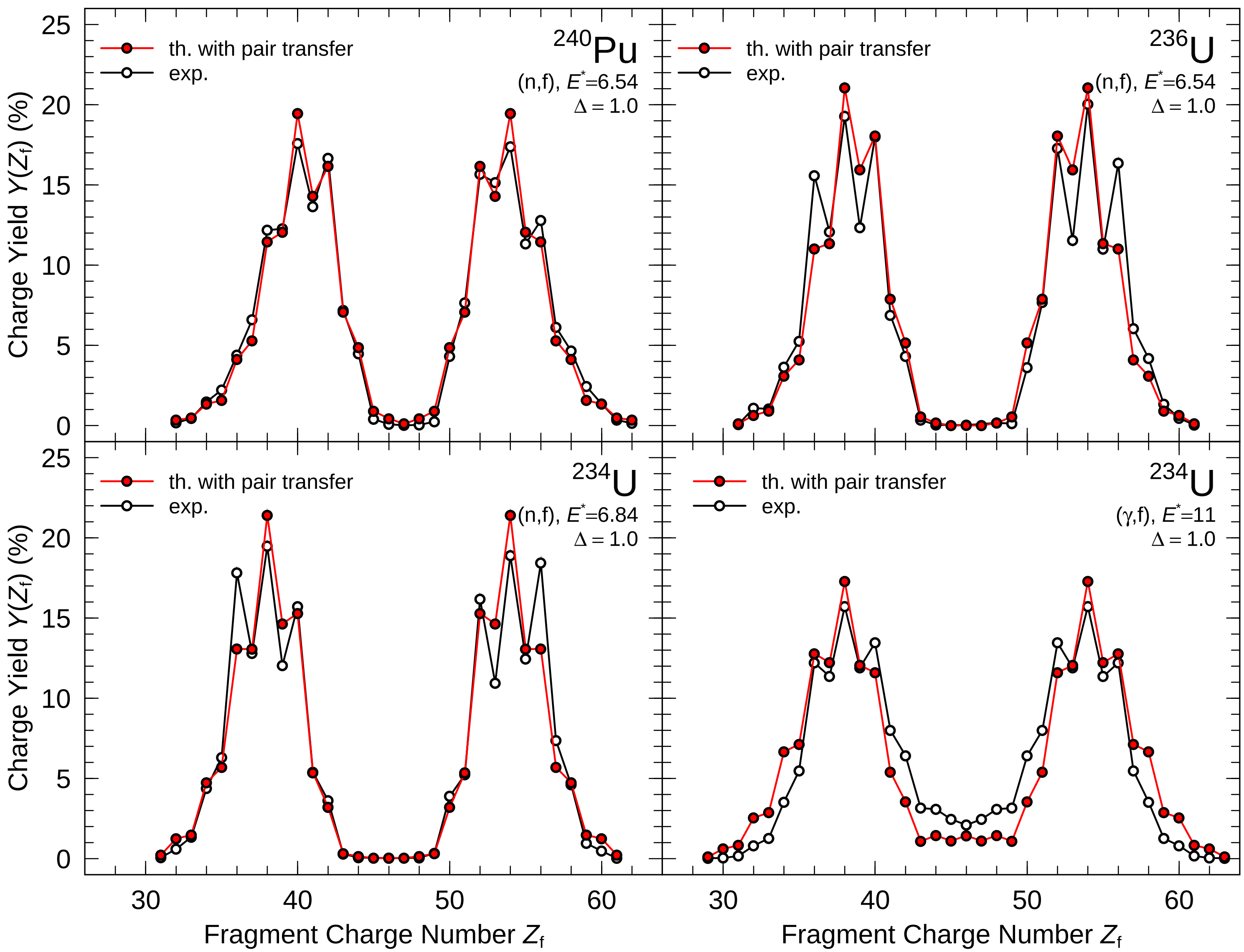
$EMAC_{Z+N}(Z_1, N_\nu, Z - Z_1, N - N_\nu) =$
$EMAC_{\text{comp}} + \Delta EMAC$

To obtain the second term calculate the sum of the macroscopic energies for the separated fragments:

$EMAC(Z_1, N_\nu) + EMAC(Z - Z_1, N - N_\nu)$

where Z_1 is fixed, N_ν varies. $\Delta EMAC$ for various N_ν (Z_1 is still fixed) is the difference between this function at N_ν and at the noninteger N corresponding to the chosen Z_1.

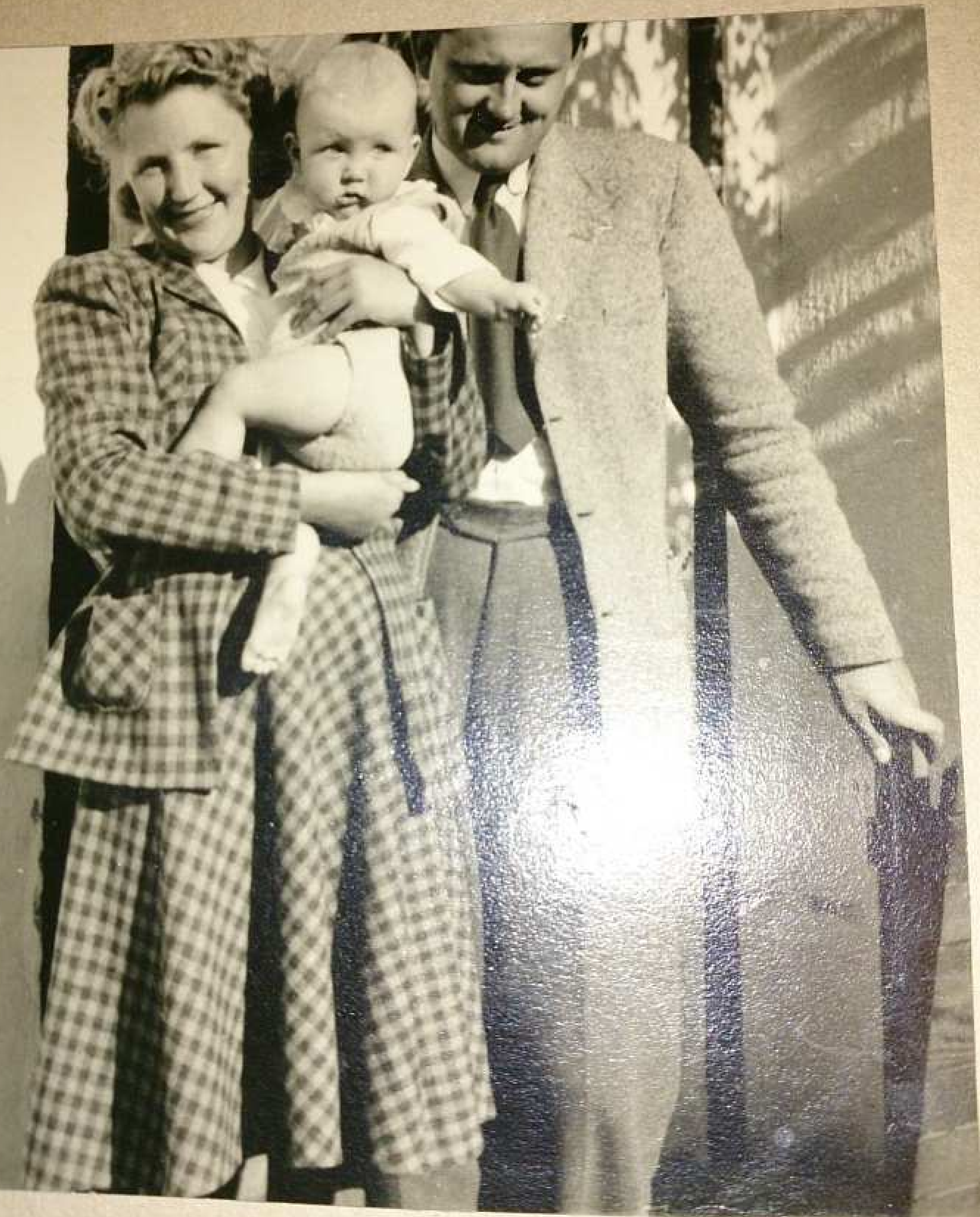

th.,no odd
exp.
240Pu
(n,f), E*=6.54
th.,no odd
exp.
236U
(n,f), E*=6.54
th., no odd
exp.
234U
(n,f), E*=6.84
th., no odd
exp.
234U
(γ,f), E*=11
Charge Yield Y(Zf) (%)
Fragment Charge Number Zf
0
5
10
15
20
25
30
40
50
60

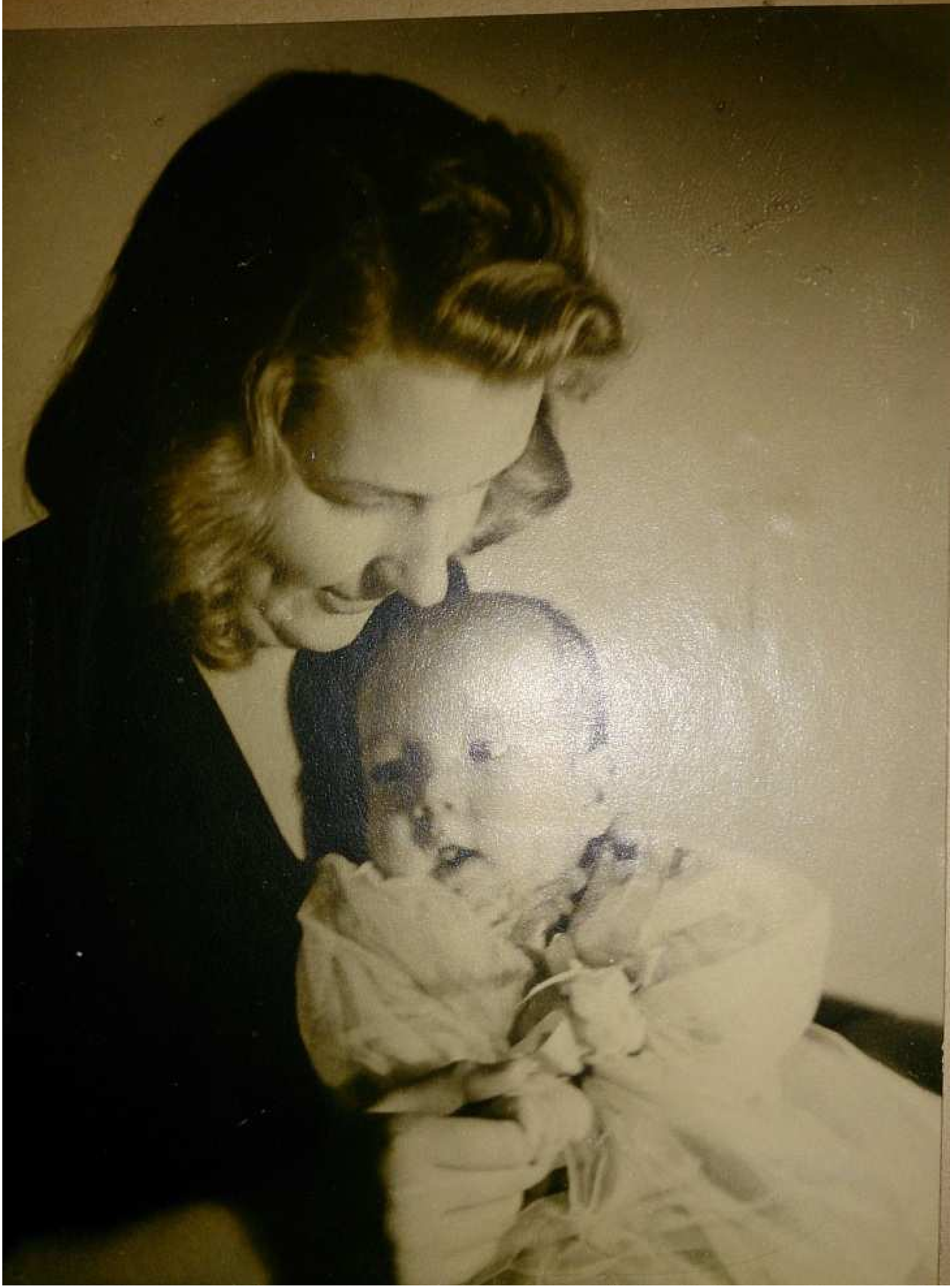


th. with pair transfer
exp.
^{240}Pu
(n,f), E^*=6.54
Δ = 1.0
^{236}U
(n,f), E^*=6.54
Δ = 1.0
^{234}U
(n,f), E^*=6.84
Δ = 1.0
^{234}U
(γ,f), E^*=11
Δ = 1.0
Charge Yield $Y(Z_f)$ (%)
Fragment Charge Number Z_f
0
5
10
15
20
25
30
40
50
60

Peter Moller, Early timeline

- Born 1944, Elem. school 1951–1955, High School 1955–1963
- Abroad: Jordan June 1957–January 1958
  Jordan June 1958–September 1958
  Kuwait November 1960–October 1961
- University: Undergraduate Oct 1963– June 1967
  Graduate 1967 – May 10 1974
  Military Service: June 68 – Aug 68 (boot camp)
  Special Military: Aug 71 – June 72
  US Visit: LBL fall 1972, LANL 12 months 1973





...rna ger ...lig resa ...rd av teak

...an, fru Inez Möller, satt ...r hon fått det ifrån är inte ...ligen just det, som präglar ...llan på Sånekullavägen.

...allt så brinnande effektiv är nu ... fru Möller — tack och lov. ... hennes duglighet och mång-...ghet är ändå nog så impone-...de. Villan, som familjen bebor, ... hon tillsammans med maken ... målat och tapetserat, alla 7 ...men har in i den minsta de-... getts en personlig touche, och ... hon sedan sköter allt hemjobb ... hör naturligtvis till bilden.

...h hobbyn på fritid är, ja, vad ... den vara om inte heminred-...

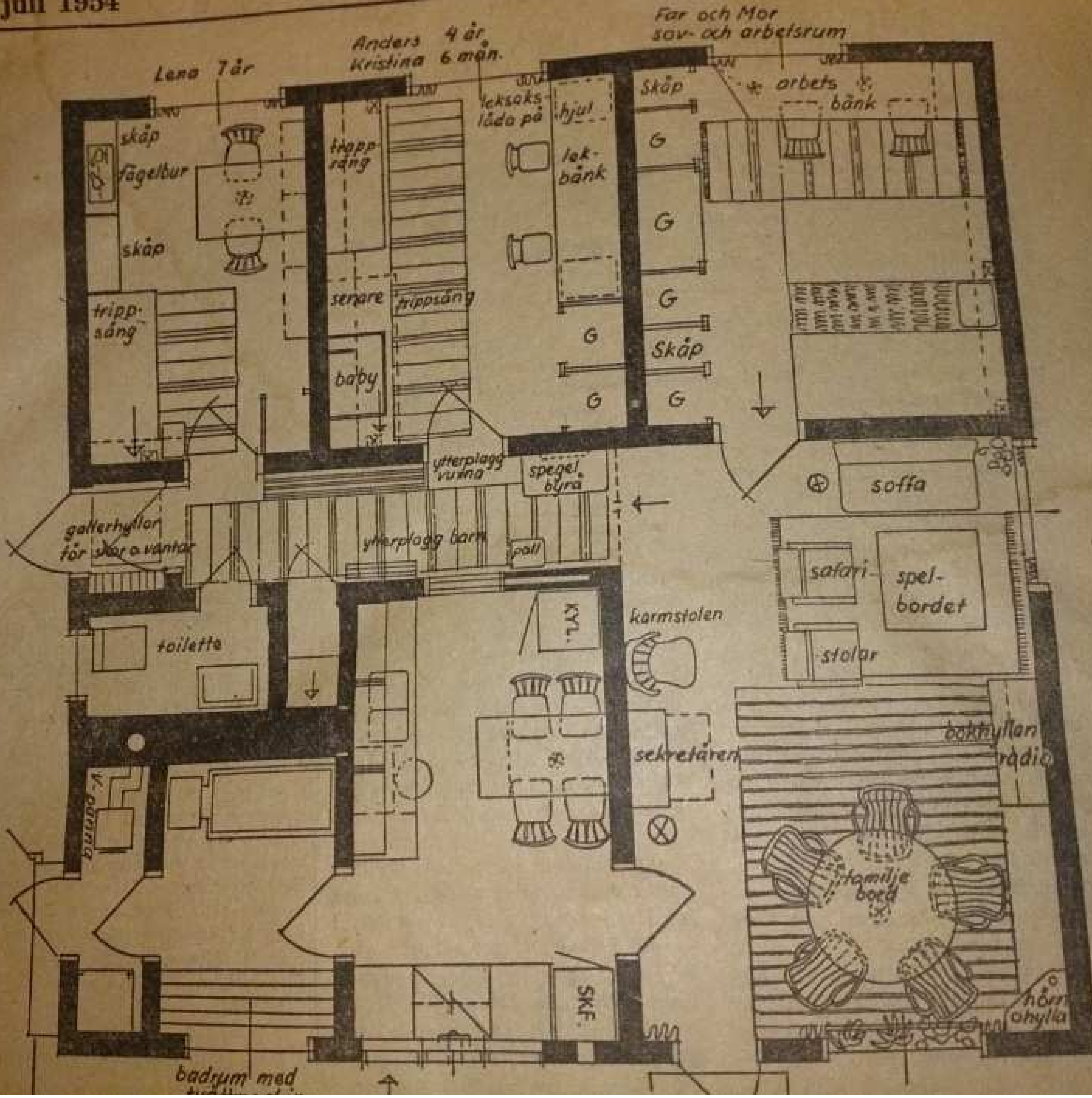
...a, jag är verkligen mycket road ...ll som har med inredning av ...em att göra, säger fru Möller. ...när man som vi gjort i ordning ... här pass stort hem har man ...lära sig att lägga ekonomiska ...unkter på inredningen. Och även ...långt man kan komma med halv-...kat, vilket kanske inte alla vet.

Var det första gången fru Möller ... i en heminredningstävling?

— Nej, det var det inte, jag har ... med i en liknande tävling förut ... fick jag faktiskt också pris.

— Och vad skall prissumman an-... till?

... det vet jag mycket bestämt




Dole
SEP 24 2003


SEP 26 2003


SEP 26 2003


SEP 27 2008


SEP 28 2003


SEP 21 2002


OCT 8 2006


OCT 15 2006


03/11/2010 21:45


03/12/2010 09:29


03/12/2010 20:59


05/27/2011 12:16


05/27/2011 12:16


08/08/2011 17:31


05/28/2012 19:42


08/14/2010 10:33


10/01/2011 16:55


10/08/2011 12:28


History
10/08/2011 12:29

RE/MAX of
Los Alamos
Your
Real Estate
Leaders
REALTY
662-5551
Today
10/08/2011 14:35


RADISH
08/24/2012 18:47


OCT 13 2003


07/07/2012 22:15


11/01/2010 19:23


11/01/2010 20:44


11/01/2010 20:44


11/01/2010 21:27