Evaluation of even-even radius parameter and ALPHAD_RadD Code

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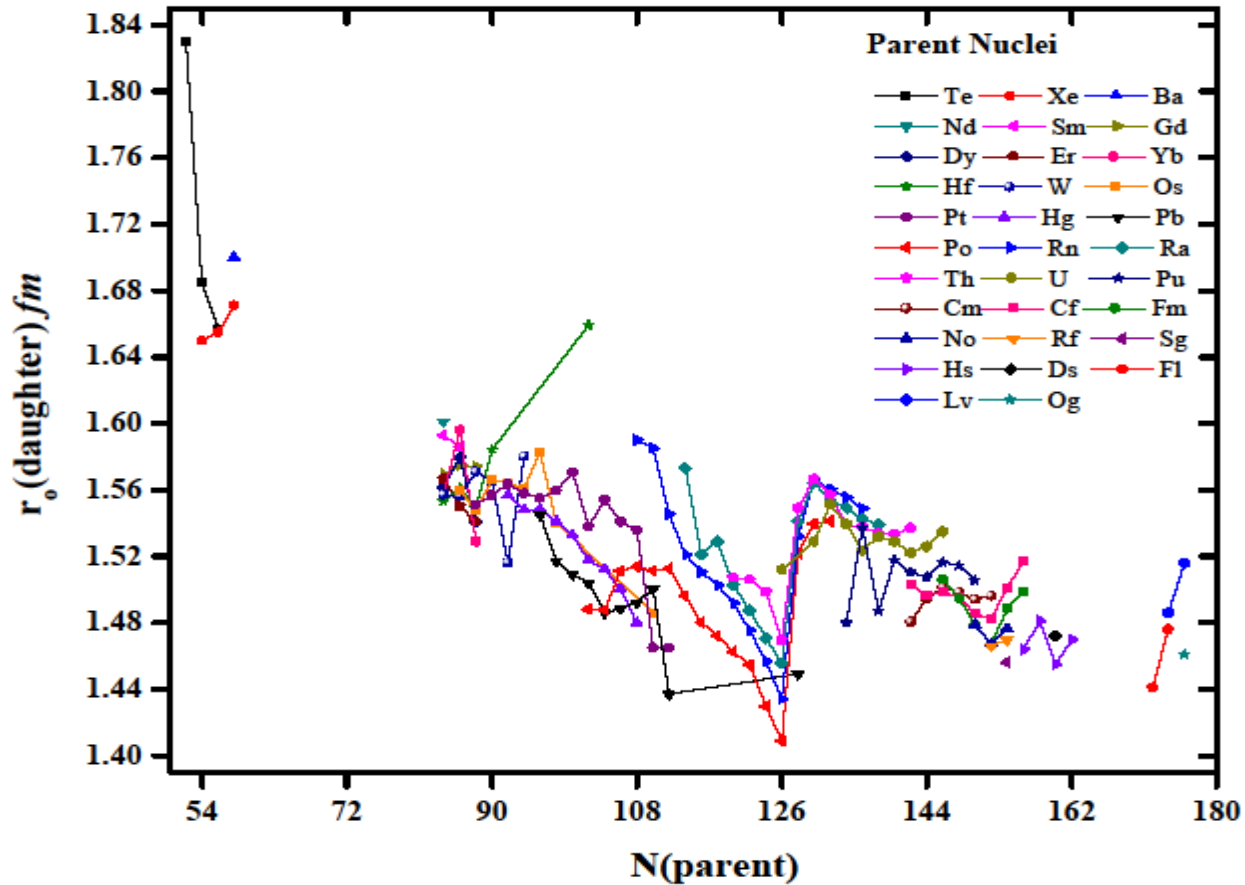Akal University, Talwandi Sabo, Bathinda, Punjab, India

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AINST, Noida, India

- Analyzed 188 even-even alpha emitters

- 26 new even-even alpha emitters added to previous evaluation

- Listed radius parameter for 186 nuclides

- 02 nuclides (^{106}Sn & ^{198}Hg) not included as $\%\alpha$ is appearing from calculations/systematics

Systematics of r0 parameters as function of parent neutron number for different Z chains.

Exhibit minima at major closed shell N=126 and increasing sharply above closed shells
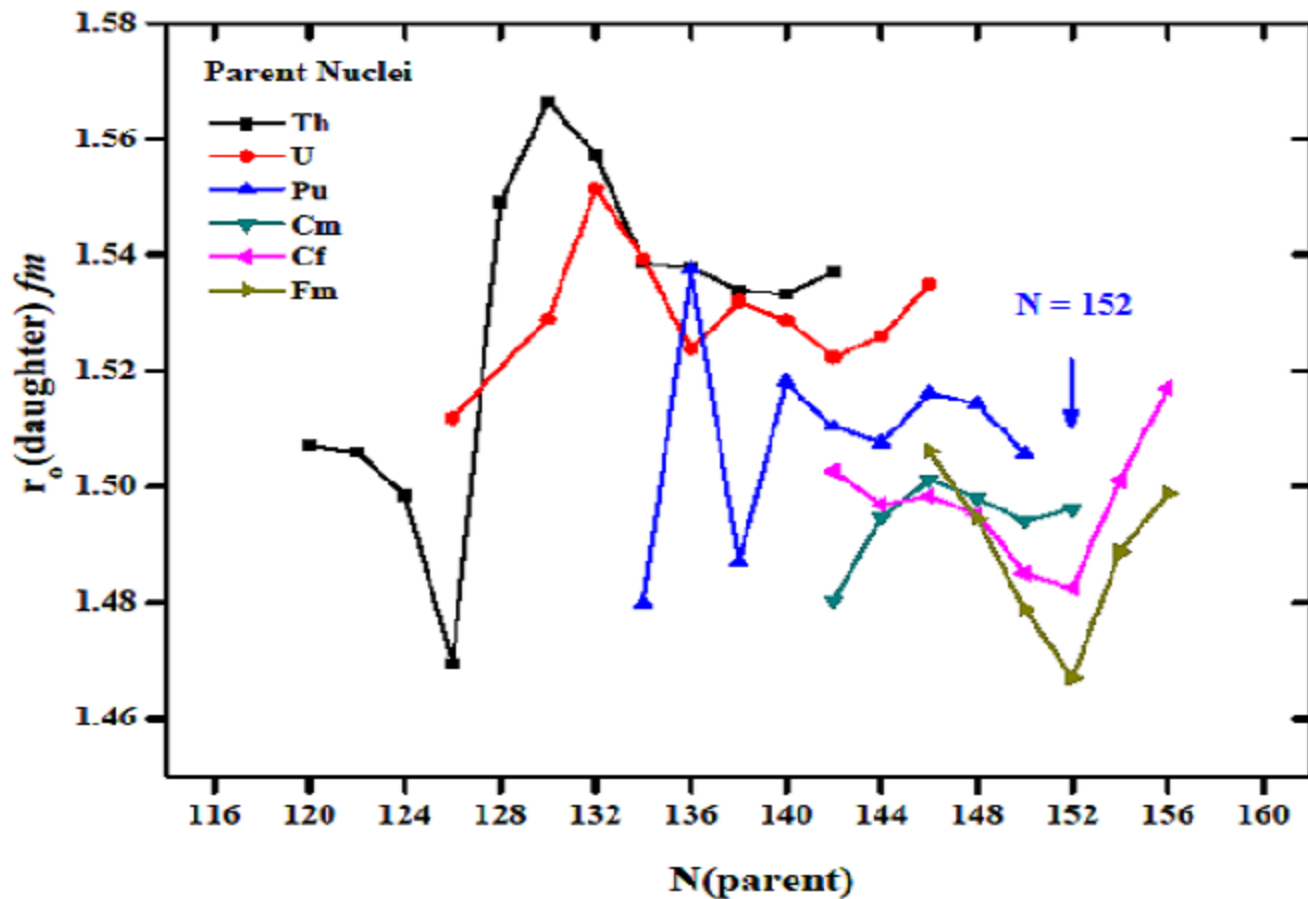
Behaviour of nuclides from Th to Cf after N(parent)=126 is different and interesting. Th, U and Pu isotopes display two minima, which keep shifting by two neutrons to the right. These minima lie at N=134 and 140 for Th, at N=136 and 142 for U, at N=138 and 144 for Pu. Thereafter Cm has a minimum at N=150, and Fm, Cf at N=152. This behaviour of shifting minima for these heavy nuclides is interesting and has not yet been explored in literature and explained on the basis of theoretical considerations.
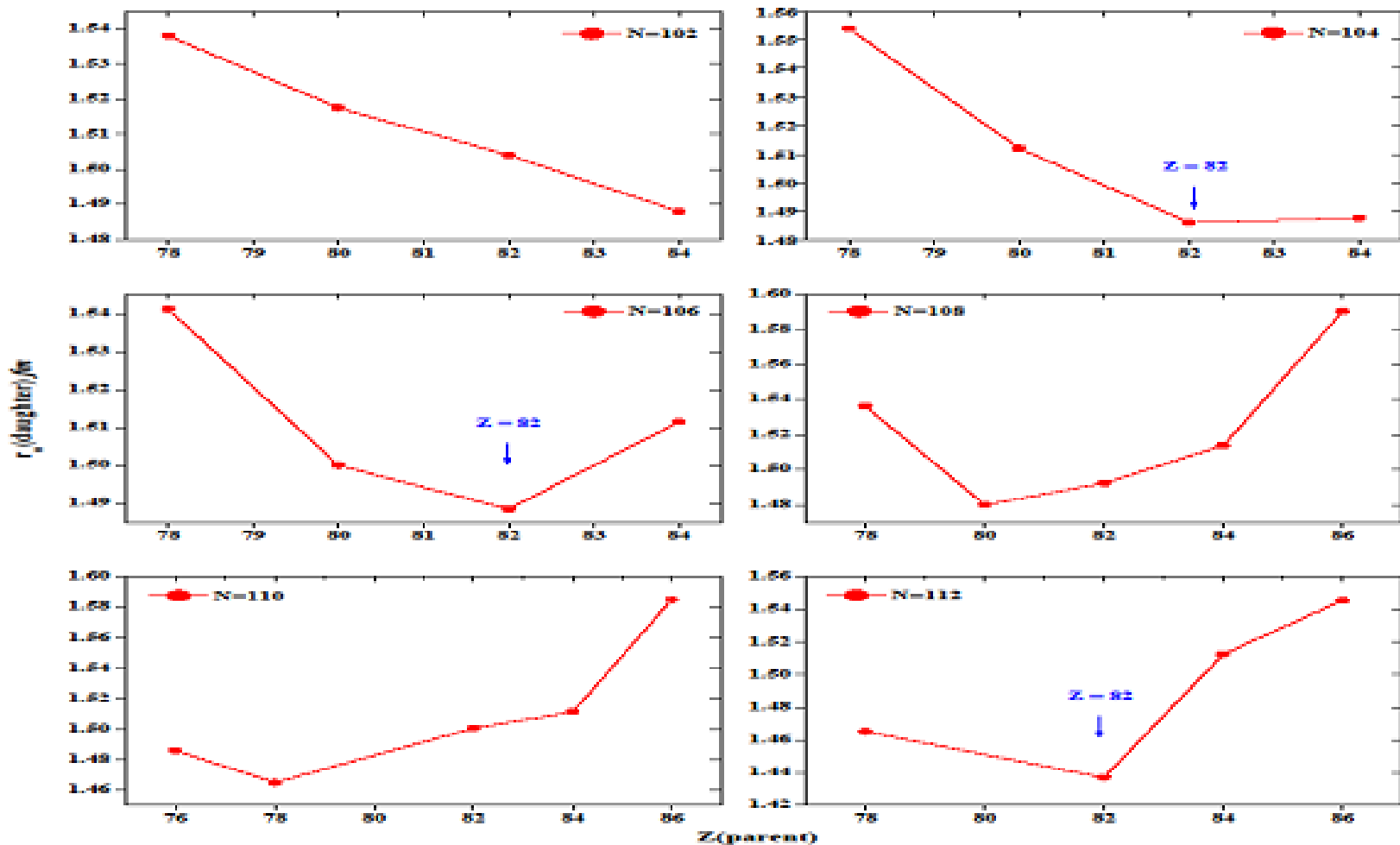
Systematic of r0 parameter as a function of proton number of parent for six isotonic chains with parent neutron numbers N=102, 104, 106, 108, 110 and 112. Isotonic chains with N=104, 106 and 112 exhibit a minima at Z=82, which indicates the role of Z=82 proton shell closure, consistent with shell model prediction of Wauters et al. [1]. However, the shell effects at Z=82 disappears for the isotonic chains with N=102, 108 and 110 as suggested by Buck et al. [2, 3] and Brown [4]. Z=82 proton shell clouser or not?

Extension of radius parameter deduction to even-odd, odd-even and odd-odd nuclei

Systematics of r0 parameters as function of parent neutron number for different Z chains of even-odd nuclei

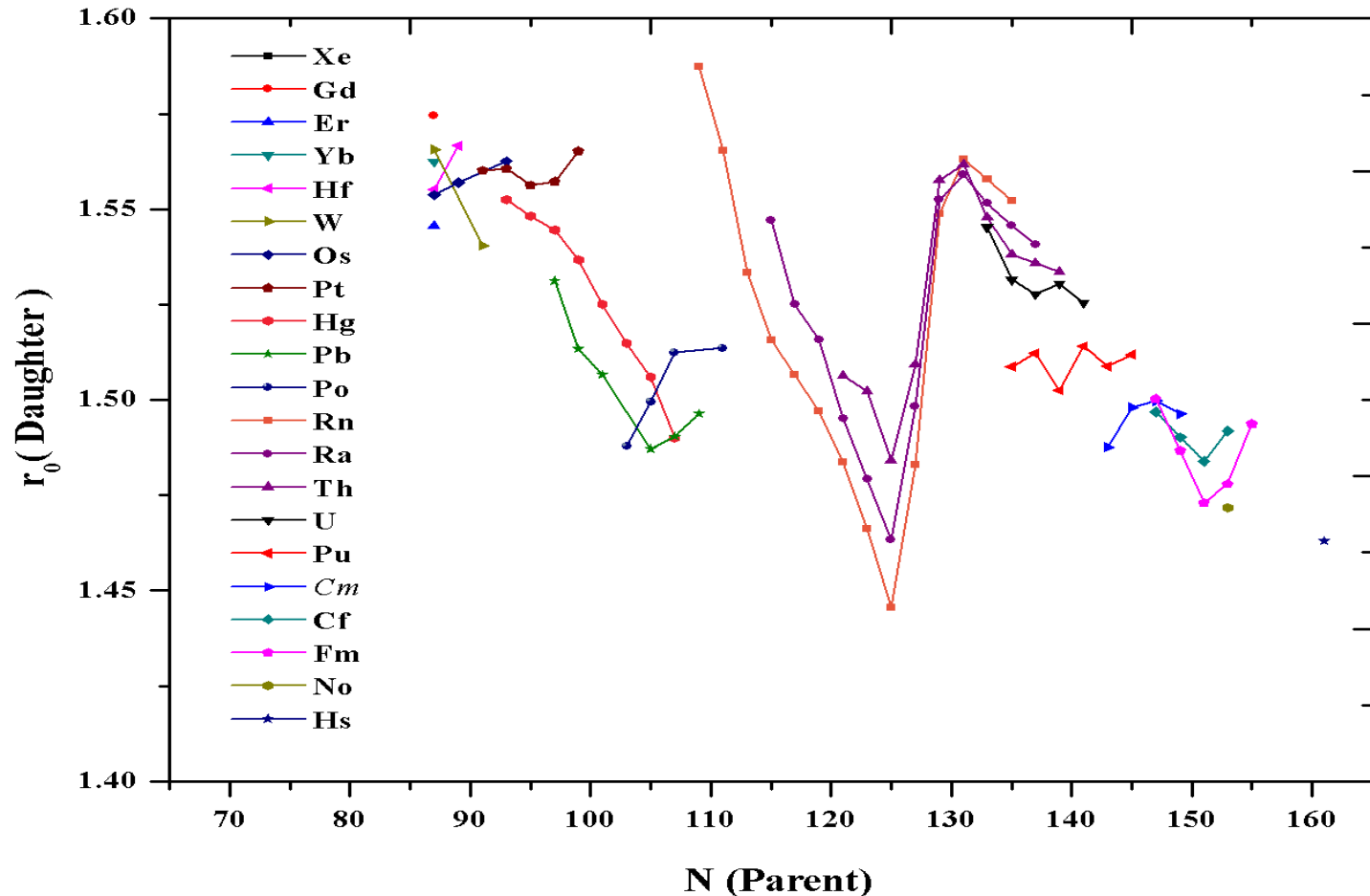Exhibit minima at major closed shell N=126 and increasing sharply above closed shells
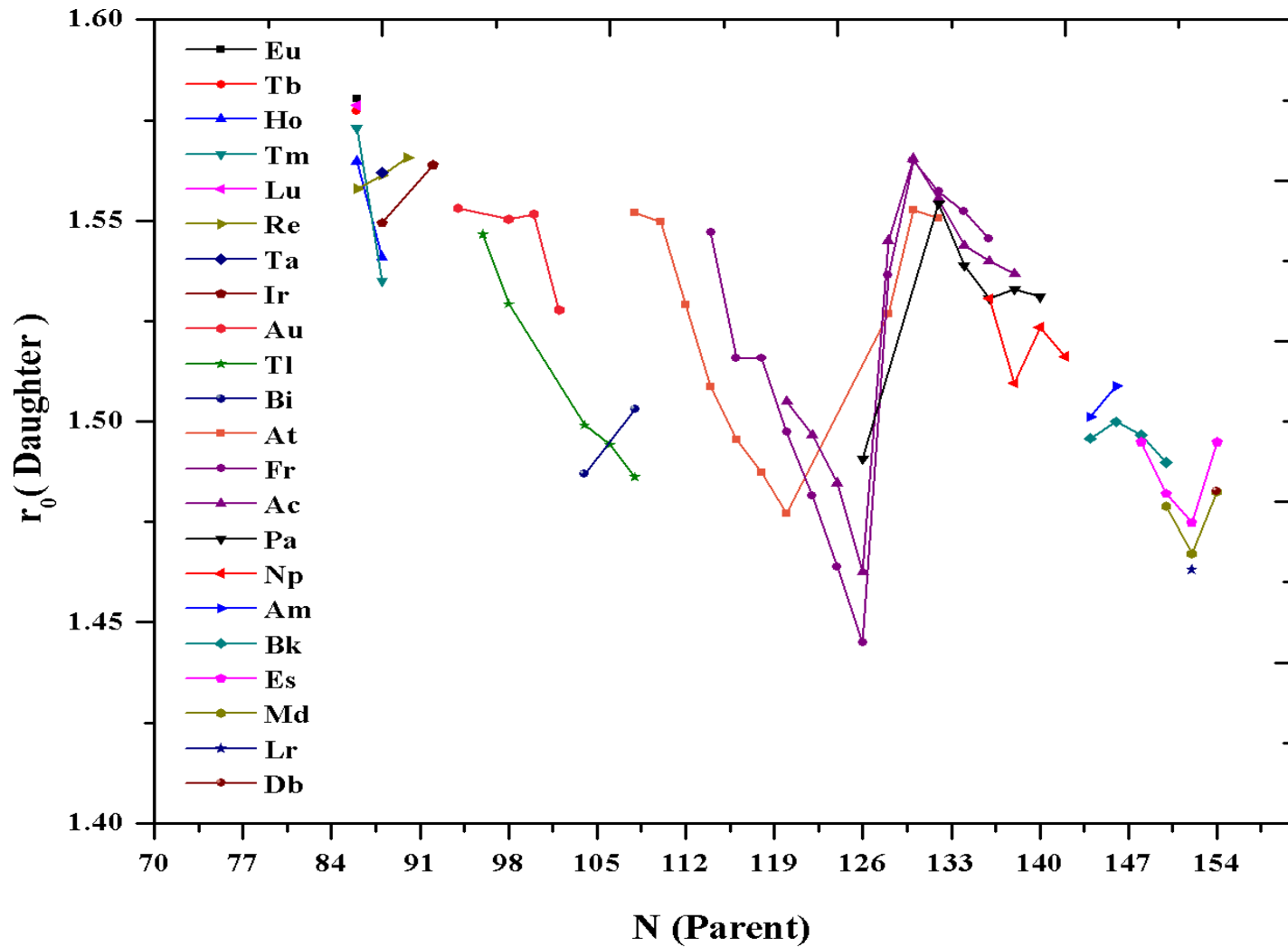
Systematics of r0 parameters as function of parent neutron number for different Z chains of odd-even nuclei
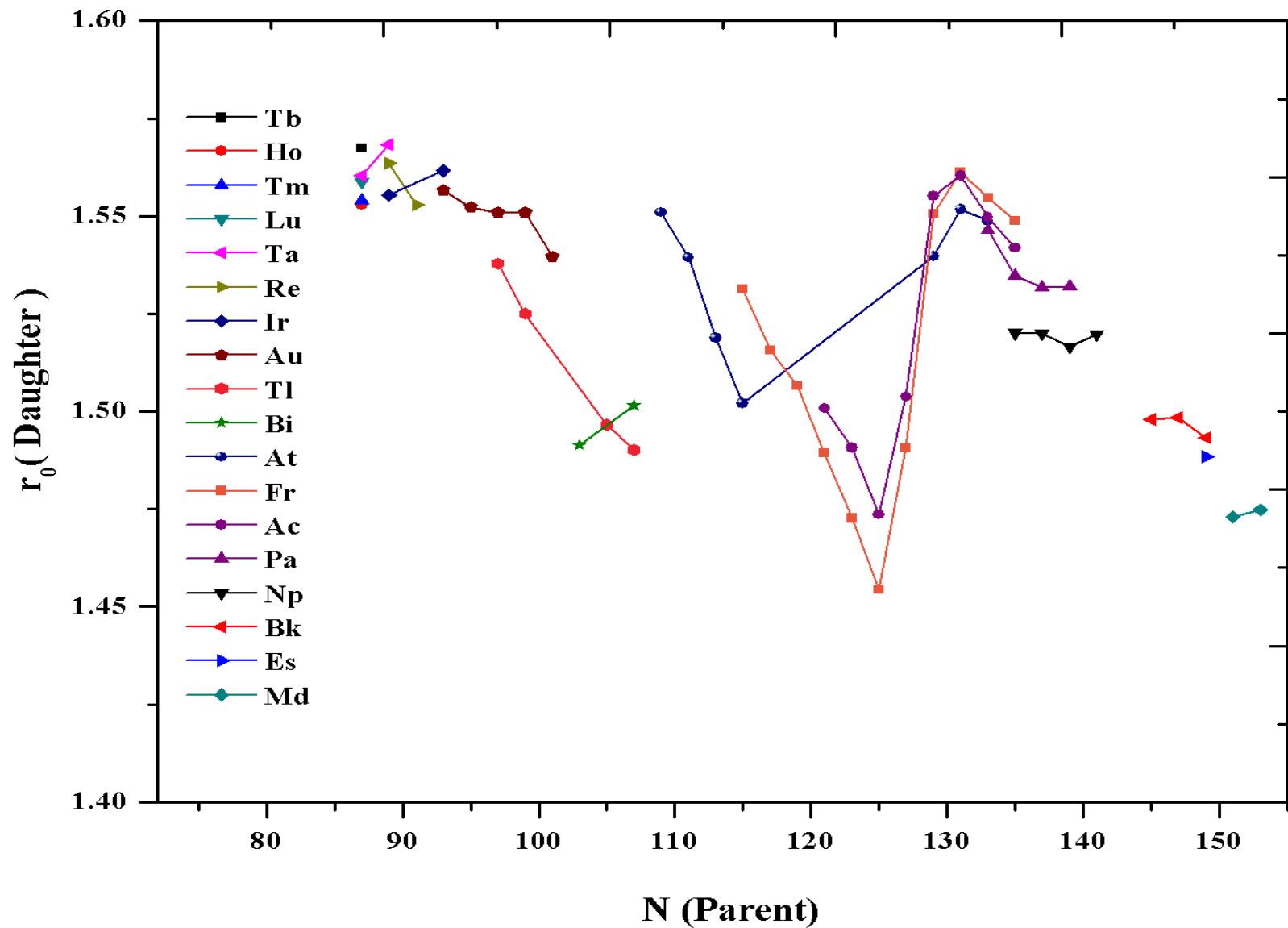
Systematics of r0 parameters as function of parent neutron number for different Z chains of odd-odd nuclei
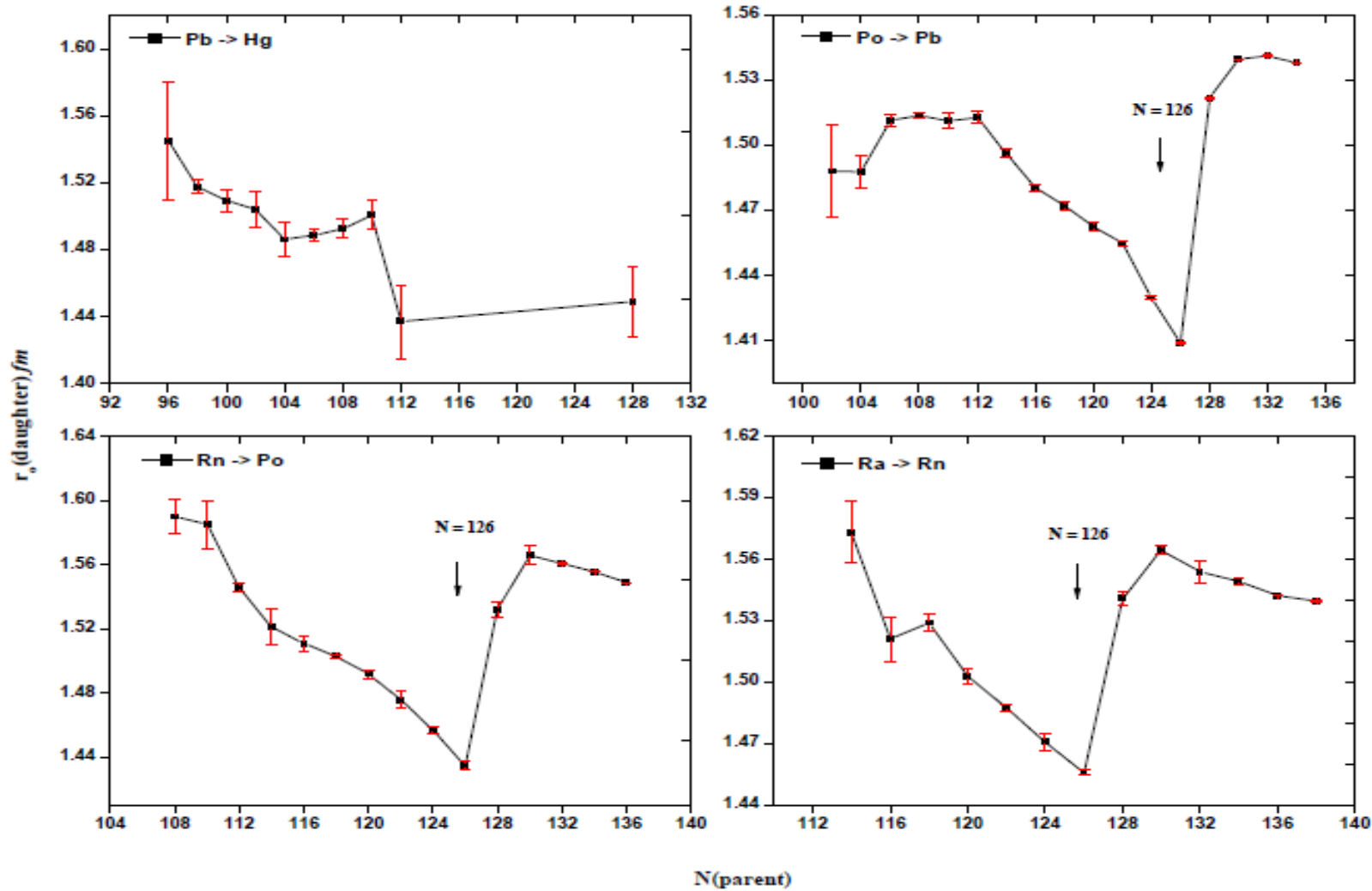
Systematics of r0 parameters as function of parent neutron number for Pb,Po, Rn and Ra nuclides. The overall uncertainty in ro is determined by propagating all the relevant uncertainties within the operation of ALPHAD.

Differences Between Original ALPHAD and ALPHAD_RadD

Even-Even Nuclides

Original ALPHAD

Calculated r_0 parameter is getting printed in ALPHAD report file, but not in ALPHAD output file. Evaluator has to insert r_0 parameter in output file manually.

ALPHAD_RadD

ALPHAD_RadD program automatically insert r_0 parameter in report as well as output file.

Position of comment lines is also fixed i.e. comment lines about radius parameter are inserted just above the parent record as:

```
210RA cA HF$The nuclear radius parameter r{-0}({+210}Ra)=1.4989 {I56}
210RA2cA is deduced by assuming HF=1.0 for the ground-state to
210RA3cA ground-state alpha decay branch.
```

Odd-Odd and Odd-A Nuclides

Original ALPHAD

The HFs and $T_{1/2}$ can be calculated, provided r_0 parameter must be supplied by user in pre-defined ENSDF below format:

R_0's may be specified on an ALPHA comment record by "HF" in columns 10 and 11 and a dollar sign ("$") in column 12 or blanks in columns 12 through 19. The first value and uncertainty in columns 20 through 80 preceded by an R (" R"; case insensitive) and an equal sign ("=") or approximate sign (" AP ") will be taken as R_0.

ALPHAD_RadD

There is no need to provide value of r_0 parameter for odd-odd and odd-A nuclides. Recently inserted RadD subroutine automatically deduces r_0 parameter for odd-odd and odd-A nuclides (using procedure of M.J. Martin [1]). The input r_0 parameters of even-even alpha emitters are taken from our recent evaluation [2] (an update of previous 1998 file by Y.A. Akovali [3]).

ALPHAD_RadD

- HFs and $T_{1/2}$ for odd-odd and odd-A nuclides are calculated and corresponding r_0 parameter is printed in output file with appropriate comment as:

```
217PO  cA HF$The nuclear radius parameter r{-0}({+217}Po)=1.55206 {I14}
217PO2cA is deduced from interpolation (or unweighted average) of radius
217PO3cA parameters of the adjacent even-even nuclides.
```

- Additionally, this program also accepts the r_0 parameter supplied by user, which later on used in the calculation of HFs and theoretical half-lives. The comments lines corresponding to given radius parameter will be inserted in output file as:

```
194BI  cA HF$The nuclear radius parameter r{-0}({+194}Bi)=1.5524 {I24}
194BI2cA as specified by the user.
```

Some recently observed issues with original ALPHAD

The original version of ALPHAD program had following problems:

- It gives unrealistically low HFs corresponding to alpha records where alpha intensity is not listed in given input ENSDF.

- Inability to handle unplaced alpha records, which leads to incorrect calculation of radius parameter (r_0) and hence Hindrance Factors.

- Unable to read official symbols of super-heavy elements Z=112-118 from input ENSDF file.

First two issues were fixed by Dr. T. Johnson at NNDC and 3rd issue along with

appearance of abundance for alpha records with missing intensities was fixed by us.

Successfully tested for different systems and submitted to IAEA on March 11, 2019 for

final testing.

Issue 1: Handling of unplaced alphas

```
234U     238PU A DECAY                        1984BO41,1970BA72              07NDS      200704
234U   H TYP=FUL$AUT=E. BROWNE, J. K. TULI$CIT=NDS 108, 681 (2007)$
234U 2 H CUT=1-Jun-2006$
234U  D  Modified by E. Browne (July 28, 2006)
238PU  P 0.0              0+                   87.7 Y    1                   5593.20    19
234U   N   1.00E-4                  1.0
234U   PN                                                                               C5
234U 2PN FOR %IG MULTIPLY BY 1.00E-4
234U   A 4579        AP      2E-5                                                         ?
234U   L 0.0              0+
234U   A 5499.03    20 70.91  10 1.0
234U  cA E         recommended in 1991Ry01 from measured energies of
234U 2cA E|a=5499.2 (1970Ba72) and E|a=5599.0 {I2} (1971Gr17).
234U  cA IA$I|a=71.8% {I11}, deduced by the evaluators from |g-ray transition
234U 2cA intensity balance.
234U  cA IA         other measured intensities are:
234U 2cA 72 (1954As07); 71.1 {I12} (1957Ko33); 72.2 (1970Ba72);
234U 3cA 70.7 {I2} (1971So15); 70.9 {I1} (1984Ah06), 71.3 {I6} (1987Bo25).
234U   L 43.4981    10 2+                      0.252 NS  7
234U   A 5456.3     3  28.98  10 1.4
234U  cA E         recommended in 1991Ry01 from measured energies of
234U 2cA E|a=5456.1 (1970Ba72) and E|a=5456.3 {I4} (1971Gr17).
234U  cA IA$I|a=28.1% {I11}, deduced by the evaluators from |g-ray transition
234U 2cA intensity balance.
```

Report File of Original ALPHAD

```
==================================
 Z:  94. A: 238. DATE RUN 01-Apr-2019 ALPHAD Version 2.0a [06-Nov-2006]
----------------------------------
Q ALPHA      E TOTAL       ALPHA HALF LIFE    RADIUS (1E-13 cm)   RZERO
5.59320 19   5.63049 19    3.203E4 D 4        5.8761 6            .953563   89
                                               R0(T+DT): 0.953527   -4
                                               R0(T-DT): 0.953600    4
                                               R0(Q+DQ): 0.953482   -8
                                               R0(Q-DQ): 0.953644    8


    TOTAL HALF LIFE    ALPHA BRANCH
     87.70 Y 10          1.000
THIS RADIUS ADJUSTED
K
ENERGY LEVEL    ALPHA ENERGY    ABUNDANCE       CALC. HALF LIFE   HINDRANCE FACTOR

0.000           4579            2.000E-7        1.6016E11 19      1.000
0.000           5499.03 20      0.7091 10       1.6016E11 24      2.8205E-7 67
43.4981 10      5456.3 3        0.2898 10       2.862E11 5        3.863E-7 16
143.352 4       5358            0.00105 5       1.1137E12 18      2.74E-5 13
296.072 4       5206            3.00E-5 10      9.590E12 16       0.000111 4
497.04 3        5015            6.8E-8 4        1.890E14 4        0.00249 15
786.288 16      4724            2.200E-7        1.913E16 4        7.611E-6 18
809.907 18      4704            5.000E-7        2.841E16 6        2.2546E-6 52
849.266 18      4662.6 4        9.E-10 4        5.530E16 11       0.0006 3
851.74 3        4661            5.93E-8 23      5.768E16 12       9.37E-6 37
926.720 15      4590            1.200E-7        2.101E17 5        1.2704E-6 30
947.64 6        4565.8 3        2.5E-9 8        3.031E17 7        4.2E-5 14
989.430 13      4524.9 4        1.300E-9        6.348E17 14       3.882E-5 10
1023.9 3        4491.1 3        1.000           1.177E18 5        2.722E-14 11
1044.536 23     4470.8 3        1.20E-8 20      1.709E18 4        1.56E-6 26
1085.26 4       4430.7 4        1.100E-8        3.595E18 8        8.100E-7 21
```

Comparison of Original ALPHAD and Revised ALPHAD (ALPHAD_V2d)

Report File of ALPHAD_V2d

```
=======================================
  Z:   94. A: 238. DATE RUN 01-Apr-2019 ALPHAD Version 2.0d [01-Aug-2018]
---------------------------------------
```

Output of Older Version of ALPHAD

Q ALPHA	E TOTAL	ALPHA HALF LIFE	RADIUS (1E-13 cm)	RZERO		RZERO	
5.59320 19	5.63049 19	3.203E4 D 4	9.2895 8	1.50749	13	.953563	89
			R0(T+DT):	1.50742	-8	0.953527	-4
			R0(T-DT):	1.50757	8	0.953600	4
			R0(Q+DQ):	1.50739	-10	0.953482	-8
			R0(Q-DQ):	1.50759	10	0.953644	8

```
         TOTAL HALF LIFE    ALPHA BRANCH
            87.70 Y 10          1.000
THIS RADIUS ADJUSTED
K
```

ENERGY LEVEL	ALPHA ENERGY	ABUNDANCE	CALC. HALF LIFE	HINDRANCE FACTOR	HINDRANCE FACTOR
0.000	5499.03 20	0.7091 10	4.517E4 9	1.000	1.000
43.4981 10	5456.3 3	0.2898 10	7.979E4 10	1.385 6	2.8205E-7 67
143.352 4	5358	0.00105 5	3.024E5 4	101 5	3.863E-7 16
296.072 4	5206	3.00E-5 10	2.501E6 4	427 15	2.74E-5 13
497.04 3	5015	6.8E-8 4	4.675E7 7	1.008E4 60	0.000111 4
786.288 16	4724	2.200E-7	4.387E9 8	33.19 7	0.00249 15
809.907 18	4704	5.000E-7	6.476E9 11	9.893 20	7.611E-6 18
849.266 18	4662.6 4	9.E-10 4	1.2473E10 21	2.9E3 13	2.2546E-6 52
851.74 3	4661	5.93E-8 23	1.3001E10 22	41.5 17	0.0006 3
926.720 15	4590	1.200E-7	4.644E10 8	5.747 12	9.37E-6 37
947.64 6	4565.8 3	2.5E-9 8	6.663E10 12	192 62	1.2704E-6 30
989.430 13	4524.9 4	1.300E-9	1.3803E11 25	178.5 4	4.2E-5 14
1023.9 3	4491.1				3.882E-5 10
1044.536 23	4470.8 3	1.20E-8 20	3.663E11 7	7.3 13	2.722E-14 11
1085.26 4	4430.7 4	1.100E-8	7.625E11 15	3.819 9	1.56E-6 26
					8.100E-7 21

```
 No IA given.
 Following record not changed.
 234U    A 4491.1    3                                               S   S
```

Issue 2: Handling of alphas with missing intensity

```
194BI     198AT A DECAY (4.1 S)              1992HU04,1996EN01,2005UU0206NDS      200606
194BI  H TYP=FUL$AUT=BALRAJ SINGH$CIT=NDS 107, 1531 (2006)$CUT=15-Apr-2006$
194BI  c  On-line mass-separated source from {+202}Fr |a decay produced by
194BI2c  Ir({+20}Ne,xn){+202}Fr and {+181}Ta({+32}S,2p9n){+202}Fr, and directly
194BI3c  by Re({+20}Ne,xn){+198}At. Measured |a particles, |g rays,
194BI4c  conversion electrons, |a|g(t) coin. Detectors: germanium, Si(Li).
194BI5c  (1992Hu04). Others: 1998Bo14, 1995BiZZ, 1988Wo11.
194BI  c  On-line mass separated (gas-filled recoil separator) source from
194BI2c  {+202}Fr |a decay produced by {+170}Yb({+35}Cl,3n) E=171-186 MeV.
194BI3c  Measured |a particles. Detector: semiconductor (1996En01).
194BI  c  {+198}At half-life is from 1992Hu04. Other value: T{-1/2}=4.6 s
194BIxc  {I+18-10} (1996En01).
194BI  c  {+198}At produced in |a decay of {+202}Fr produced in
194BI2c  {+141}Pr({+63}Cu,P{-n}) E=278-288 MeV and in {+170}Yb({+36}Ar,p3n)
194BIxc  E=180-185 MeV (2005Uu02,2005Uu03)
194BI cA HF          r{-0}=1.515 fm
198AT  P 0.0               (3+)                4.1 S     3               6893.0  22
198AT cP T$ from timing of |a decay, weighted average of 3.8 s {I4} (2005Uu02)
198AT2cP and 4.2 s {I3} (1992Hu04). Other: 4.9 s {I5} (1967Tr06).
194BI  N                               0.97 3
194BI cN BR$ from %|a|>94 (1995BiZZ). Others: %|a=76 {I21} (1998Bo14),
194BI2cN >80 (1992Hu04), >90 (1980Ew03).
194BI2cN 2002Zh04 evaluation quotes 0.90 {I10} from %|a>80 (1992Hu04)
194BI  L 0.0               (3+)
194BI  A 6753        4   100        2.5
194BI cA E$weighted average of 6748 {I6} (2005Uu02), 6753 {I4} (1996En01)
194BI2cA and 6755 {I4} (1992Hu04).
194BI3cA Others: 6747 {I5} (1967Tr06), 6747 {I15} (1980Ew03), 6755 (1995BiZZ)
194BI  L 218          1
194BI  A 6539          10
194BI  G 218          1
194BI  L 396          1
194BI  A 6360          10 0.34    5 23
194BI  G 181          1
```

Report File of Original ALPHAD

```
194BI    198AT A DECAY (4.1 S)              1992HU04,1996EN01,2005UU0206NDS    200606
194BI  H TYP=FUL$AUT=BALRAJ SINGH$CIT=NDS 107, 1531 (2006)$CUT=15-Apr-2006$
194BI  c On-line mass-separated source from {+202}Fr |a decay produced by
194BI2c   Ir({+20}Ne,xn){+202}Fr and {+181}Ta({+32}S,2p9n){+202}Fr, and directly
194BI3c   by Re({+20}Ne,xn){+198}At. Measured |a particles, |g rays,
194BI4c   conversion electrons, |a|g(t) coin. Detectors: germanium, Si(Li).
194BI cA HF          r{-0}=1.515 fm
198AT  P 0.0            (3+)                   4.1 S      3              6893.0  22
198AT cP T$ from timing of |a decay, weighted average of 3.8 s {I4} (2005Uu02)
198AT2cP and 4.2 s {I3} (1992Hu04). Other: 4.9 s {I5} (1967Tr06).
194BI  N                           0.97 3
194BI cN BR$ from %|a|>94 (1995BiZZ). Others: %|a=76 {I21} (1998Bo14),
194BI2cN >80 (1992Hu04), >90 (1980Ew03).
194BI2cN 2002Zh04 evaluation quotes 0.90 {I10} from %|a>80 (1992Hu04)
194BI  L 0.0            (3+)
194BI  A 6753        4  100       2.5
194BI cA E$weighted average of 6748 {I6} (2005Uu02), 6753 {I4} (1996En01)
194BI2cA and 6755 {I4} (1992Hu04).
194BI3cA Others: 6747 {I5} (1967Tr06), 6747 {I15} (1980Ew03), 6755 (1995BiZZ)
194BI  L 218          1
194BI  A 6539         10
194BI  G 218          1
194BI  L 396          1
194BI  A 6360         10 0.34    5 23
194BI  G 181          1

======================================
  Z:  85. A: 198. DATE RUN 01-Apr-2019 |ALPHAD Version 2.0a [06-Nov-2006]|
--------------------------------------
Q ALPHA       E TOTAL       ALPHA HALF LIFE    RADIUS (1E-13 cm)  RZERO
6.8930 22     6.9253 22     4.9E-5 D 4         8.770             1.515

    TOTAL HALF LIFE    ALPHA BRANCH
    4.1 S 3            0.97 3
K
ENERGY LEVEL   ALPHA ENERGY    ABUNDANCE       CALC. HALF LIFE   HINDRANCE FACTOR

    0.000         6753 4         1.000          2.138E-5 16        2.29 19
    218.0 10      6539 10        1.000          0.0001404 13       0.35 3
    396.0 10      6360 10        0.0034 5       0.000703 7         20 4
    No IA given.
    Following record not changed.
    194BI  A 6539          10
```

Comparison of results of original ALPHAD and ALPHAD_V2d

Report File of Older Version of ALPHAD

```
========================================
 Z:   85. A: 198. DATE RUN 01-Apr-2019 ALPHAD Version 2.0a [06-Nov-2006]
----------------------------------------
Q ALPHA        E TOTAL        ALPHA HALF LIFE      RADIUS (1E-13 cm)   RZERO
6.8930 22    6.9253 22      4.9E-5 D 4           8.770               1.515

    TOTAL HALF LIFE      ALPHA BRANCH
    4.1 S 3              0.97 3
K
ENERGY LEVEL   ALPHA ENERGY     ABUNDANCE        CALC. HALF LIFE   HINDRANCE FACTOR

    0.000            6753 4           1.000            2.138E-5 16        2.29 19
    218.0 10         6539 10          1.000            0.0001404 13       0.35 3
    396.0 10         6360 10          0.0034 5         0.000703 7         20 4
    No IA given.
    Following record not changed.
    194BI   A 6539          10
```

Report File of ALPHAD_V2d

```
========================================
 Z:   85. A: 198. DATE RUN 01-Apr-2019 ALPHAD Version 2.0d [01-Aug-2018]
----------------------------------------
Q ALPHA        E TOTAL        ALPHA HALF LIFE      RADIUS (1E-13 cm)   RZERO
6.8930 22    6.9253 22      4.9E-5 D 4           8.770               1.515

    TOTAL HALF LIFE      ALPHA BRANCH
    4.1 S 3              0.97 3
K
ENERGY LEVEL   ALPHA ENERGY     ABUNDANCE        CALC. HALF LIFE   HINDRANCE FACTOR

    0.000            6753 4           1.000            2.138E-5 16        2.29 19
    218.0 10         6539            
    396.0 10         6360 10          0.0034 5         0.000703 7         20 4
    No IA given.
    Following record not changed.
    194BI   A 6539          10
```

ALPHAD_RadD_v1.1

Revised ALPHAD then successfully re-welded with RadD subroutine to automatize the radius parameter deduction procedure and hence calculation of HFs.

All the above mentioned issues have been successfully fixed in latest version of ALPHAD_RadD_v1.1, and revised code has been submitted to IAEA, Vienna.

Future Plans for Improvement of ALPHAD and ALPHAD_RadD

1. Asymmetric uncertainty in half-lives of parent: At present only the first uncertainty in the half-life of parent is being used in the calculation of radius parameter.

   Option-1: program must have some logic to use both upper and lower   uncertainty should be used by program in calculation

<div align="center">or</div>

   Option-2: It should first converted to symmetric uncertainty and then should be used in further calculations.

2. ALPHAD_RadD program does not have any logic to replace the previous statement about r_0 parameter with the newly generated statement in the ALPHAD output file. Probably not possible with code to delete earlier comment : position and number of lines containing ro parameter comment varies in input ENSDF files.

   Better to delete earlier ro comment lines manually.

The alpha decay data sets, containing asymmetric uncertainties of parent half life and executed through earlier version ALPHAD, should be checked as earlier version of ALPHAD consider only half-life value with first (+ve) uncertainty.

Acknowledgement :

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DAE-BRNS, Mumbai (India)

IAEA, Vienna