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Alpha Decay Half-Lives of Heavy Nuclei

Czasy życia jąder ciężkich ze względu na rozpad α

1. INTRODUCTION

During the last few years, the number of known α emitters has been increased, especially in the transuranium region [1–7]. It demands a continuing progress in the theoretical description of these phenomena and in predictions of properties for nuclei still unknown.

The α decay competes usually with fission in the disintegration of the heaviest nuclei synthesized in heavy ion reactions. Therefore it is crucial to estimate the partial half-life of nuclei with respect to these processes. There are many theoretical calculations of spontaneous fission half-lives, based on the Nilsson (see e.g. [8]) or Woods–Saxon (e.g. [9]) single particle potentials. Some papers [10,12] give also results for α and β decay, based on various semiempirical formulae. One can find many of these relationships in the literature [13–19]. Their parameters have been determined by fitting to known experimental data. Consequently it is interesting to see the agreement with experiment and to compare the results from various formulae.

The main subject of this paper is to examine seven different formulae of the α decay half-life. The basis for calculations was a realistic Woods–Saxon potential [20]. It gives the good nuclear masses, hence values of energies released in α emission, and other characteristics of nuclei.

The potential energy was calculated by the Strutinsky method [21]. Nonaxial degrees of freedom of the nuclear shape as well as blocking effect in short range correlations for odd-even/odd systems were taken into account.

Even-even, odd-even, even-odd and odd-odd nuclei with proton number Z=96–111 are considered. The method of the calculations is described in Section 2. The results are presented in the table which contains α decay half-lives from seven known formulae and for two sets of parameters called "Old" and "New".

2. METHOD OF CALCULATION

To generate the single-particle spectrum, we use the Woods–Saxon potential [20]. Nonaxial degrees of freedom of the nuclear shape are taken into account. The blocking effect in short-range correlations for odd-even and odd-odd systems is assumed. The potential energy is calculated by the Strutinsky method [21] and a smooth energy is identified with the liquid drop energy E_{LD} [22]

$$E(\hat{\beta}) = E_{LD}(\hat{\beta}) + \delta E_{shell}(\hat{\beta}) + \delta E_{pair}(\hat{\beta}) \,, \tag{1}$$

where $\hat{\beta}$ is the deformation space: $\hat{\beta} = [\beta_2, \beta_4, \gamma]$. From the phenomenology of the α–decay one knows that the half-life with respect to α emission depends strongly upon the energy released in the process. The decay energy is equal to the difference of the ground state masses of nuclei involved. The ground state masses in turn are obtained from the minimum of the nuclear potential energy of deformation. The mass of $\mathcal{M}(Z,N)$ nucleus is:

$$\mathcal{M}(Z,N) = \mathcal{M}_{LD}(Z,N) + \frac{1}{c^2} E_{eq}(Z,N) \,, \tag{2}$$

where $\mathcal{M}_{LD}$ denotes the mass of the spherical liquid-drop model and E_{eq} is the energy of the nucleus (eq. 1) at equilibrium deformation $\hat{\beta}_{eq}$

$$E_{eq} = E(\hat{\beta}_{eq}) \,. \tag{3}$$

The energy released when the nucleus (Z, N) emits an α particle is:

$$Q_\alpha(Z,N) = [\mathcal{M}(Z,N) - \mathcal{M}(Z-2,N-2) - \mathcal{M}(2,2)]c^2 \,. \tag{4}$$

The main subject of this paper is to calculate the α–decay half-lives (T_α) of even-even, even-odd and odd-odd actinide nuclei with $96 \leq Z \leq 111$. The α decay of the nucleus in the considered region may compete effectively with spontaneous fission or may be even faster than it [9].

Further on we present formulae used in calculations.

The formula given by Fröman [13] reads:

$$\log T_\alpha = [139.8 + 1.83z + 0.012z^2]/\sqrt{Q_\alpha} - 0.3z - 0.001z^2 + C_F\,, \quad (5)$$

where $z = Z - 90$, and Q_α-values are expressed in MeV and T_α in seconds.

The second formula introduced by Wapstra et al. [14] is:

$$\log T_\alpha = (1.2Z + 34.9)/\sqrt{Q_\alpha} + C_W\,. \quad (6)$$

The two next relationships (very similar) were presented by Taagepara and Nurmia [15]

$$\log T_\alpha = 1.61[Z_d/\sqrt{Q_\alpha} - Z_d^{2/3}] + C_T\,, \quad (7)$$

and by Keller and Münzel [16]

$$\log T_\alpha = H_K[Z_d/\sqrt{Q_\alpha} - Z_d^{2/3} + C_K\,. \quad (8)$$

where $Z_d = Z - 2$ is the atomic number of the daughter nucleus, $H_k = 1.61$ for even-even; 1.65 for even-odd; 1.66 for odd-even and 1.77 for odd-odd nuclei.

The equation given by Viola and Seaborg [18] is of the form

$$\log T_\alpha = A_Z/\sqrt{Q_\alpha} + B_Z + C_V\,, \quad (9)$$

where

$$A_Z = 2.113292Z - 48.9879\,, \quad (10)$$

and

$$B_Z = -0.3900402Z - 16.9543\,. \quad (11)$$

Hornshøj et al. [17] have proposed the following formula:

$$\log T_\alpha = 0.80307\left(\frac{A_d^{4/3}Z_d}{A}\right)^{\frac{1}{2}}\left((\frac{\arccos\sqrt{x}}{\sqrt{x}} - \sqrt{1-x}\right) + C_H\,, \quad (12)$$

in which $x = 0.538243QA_d^{1/3}/Z_d$. Z_d and A_d are the atomic and mass number of the daughter nucleus respectively.

The last formula derived by Poenaru and Ivascu [19] reads

$$\log T_\alpha = \chi K_s ln 10 - 20.446\,, \quad (13)$$

where

$$K_S = 2.52956 Z_d(\frac{A_d}{AQ_\alpha})^{1/2}[\arccos\sqrt{x} - \sqrt{x(1-x)}]\,, \quad (14)$$

and

$$x = 0.4253Q_\alpha(1.5843 + A_d^{1/3})/Z_d\,. \tag{15}$$

The value of χ is different for various nuclei (see [19], eqs 17–19).

The parameters C, in the "Old" or "New" version used in calculations are taken from paper [19] and are shown in Table 1.

Table 1. "Old" and "New" values of C_k parameters*

Tab. 1. Zestaw parametrów C_K użytych w obliczeniach czasów życia T_α

	even-even		odd-even		even-odd		odd-odd	
k	*Old*	*New*	*Old*	*New*	*Old*	*New*	*Old*	*New*
FR	52.3	51.699	52.3	51.317	52.3	51.299	52.3	50.705
WA	53.	52.400	53.	52.026	53.	51.940	53.	51.377
TN	21.02	20.789	20.64	20.470	20.86	20.346	20.33	19.758
KM	20.2	20.226	20.7	20.643	20.5	20.383	20.8	20.571
VS	0	0.043	−0.772	−0.196	−1.066	−0.339	−1.114	−0.962
HO	20.279	20.347	20.279	20.051	20.279	19.922	20.279	19.355

* C-parameters are taken from Poenaru and Ivascu paper [19].

3. FIGURES

For illustration the calculated and experimental values of Q_α are displayed in Figure 1. The reasonable agreement of experimental and theoretical Q's may be seen. The biggest discrepancy between experimental and theoretical Q-value equals to 1 MeV and is observed for a few cases only.

All results of calculations with the formula of Viola–Seaborg for even-even (E–E), even-odd (E–O), odd-even (O–E) and odd-odd (O–O) nuclei are shown in Figures 2 to 5. The left upper and the right-lower corners of each figure represent extrapolated and therefore rough values of $\log(T_\alpha)$ and should not be taken into account.

4. TABLES

The α decay Q–values and α–half-life times were calculated for a large class of the heaviest nuclei with Z = 96–111. The results are presented in Table 2. The table contains the atomic number (Z) and the mass number (A) of the nucleus, Q_α value, both experimental (Q^{exp}) and theoretical (Q^{th}) and eight values of decimal logarithm of the α-half-life (T_α) denoted as EXP (experimental value), VS (for Viola and Seaborg), TN (Taagepara and Nurmia), FR (Fröman), WA (Wapstra et al.), HO (Hornshøj), KM (Keller and Münzel), PI (Poenaru and Ivascu).

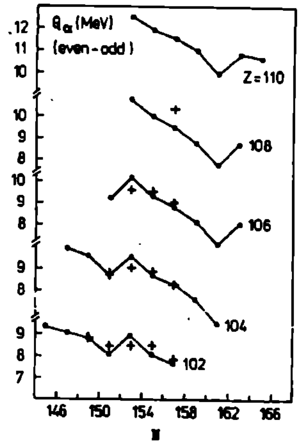

Fig. 1. Experimental and theoretical α-decay energies Q_α. The theoretical data are depicted by crosses

Ryc. 1. Teoretyczne i eksperymentalne wartości ciepła reakcji Q_α. Krzyżykami oznaczono dane teoretyczne

The first line of each data block consists of $\log(T_\alpha)$ for "old" values of C_k parameters while the second line contains the similar data for new values of C_k (see Table 1). Here k takes the meaning VS, TN, FR, WA, HO, KM. The lowest values of $T \log T_\alpha$ are given by the formula by Fröman and the largest values are obtained on the basis of the Viola and Seaborg prescription. The difference between both $\log T_\alpha$'s values oscillates in the interval 1.5–2. All other formulas give $\log T_\alpha$ between both values quoted above.

The last column of Table 2 represents the values of $\log T_\alpha$ as calculated according to formula given by Poenaru and Ivascu [19] shown in eq 13.

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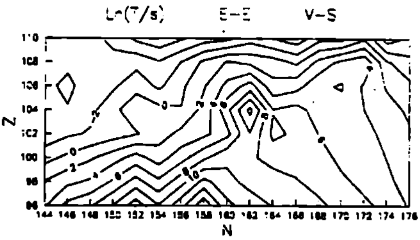

·Fig. 2. Logarithms of α-decay half lives of even-even nuclei

Ryc. 2. Logarytmy czasów połowicznego rozpadu T_{α} dla jąder parzysto-parzystych (E–E) uzyskane z formuły Viola–Seaborg (V–S)

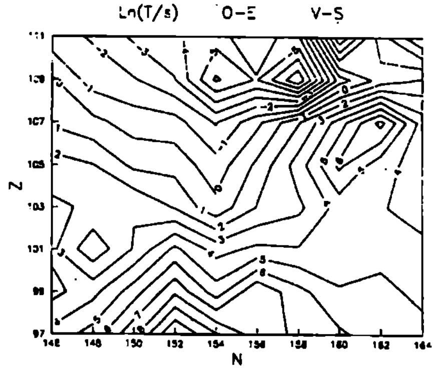

Fig. 3. Logarithms of α-decay half lives of odd-even nuclei

Ryc. 3. Tak, jak na Ryc. 2, ale dla jąder parzysto-nieparzystych (E–O)

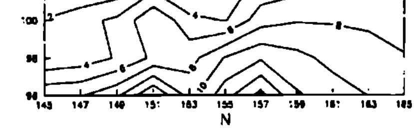

Fig. 4. Logarithms of α-decay half lives of even-odd nuclei

Ryc. 4. Tak, jak na Ryc. 2, ale dla jąder nieparzysto-parzystych (O–E)

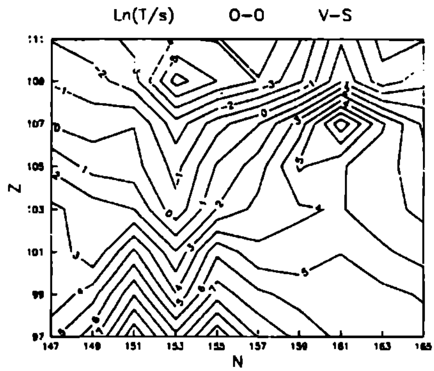

Fig. 5. Logarithms of α-decay half lives of odd-odd nuclei

Ryc. 5. Tak, jak na Ryc. 2, ale dla jąder nieparzysto-nieparzystych (O–O)

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STRESZCZENIE

Wykorzystując jednocząstkowy potencjał typu Woodsa–Saxona obliczono czasy życia jąder aktynowców ze względu na rozpad α. W obliczeniach uwzględniono wszystkie jądra, tj. parzysto-parzyste, nieparzysto-parzyste, parzysto-nieparzyste, jak i nieparzysto-nieparzyste. Przetestowano siedem różnych formuł występujących w literaturze. Niniejszy artykuł daje pełny przegląd T_α dla jąder z obszaru $96 \leqslant Z \leqslant 111$.

Table 2. Logarithms of α half lives
Tab. 2. Logarytmy czasów życia T_α dla siedmiu różnych formuł, występujących w literaturze

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
96	241	6.19	6.37	8.60	7.57	6.31	5.76	6.46	6.30	7.00	
					6.90	6.82	6.77	7.52	6.65	7.11	6.80
96	242	6.22	6.36	7.30	6.62	6.21	5.83	6.52	6.34	6.53	
					6.58	6.44	6.43	7.12	6.27	6.50	6.46
96	243	6.17	6.32	9.10	7.84	6.58	6.03	6.73	6.52	7.27	
					7.17	7.09	7.03	7.79	6.88	7.39	7.11
96	244	5.90	6.13	8.90	7.75	7.32	6.93	7.62	7.41	7.63	
					7.71	7.55	7.53	8.22	7.34	7.61	7.58
96	245	5.62	5.98	11.50	9.56	8.27	7.72	8.40	8.18	9.01	
					8.89	8.79	8.72	9.46	8.54	9.13	8.91
96	246	5.48	5.70	11.30	10.06	9.60	9.20	9.87	9.66	9.90	
					10.01	9.84	9.80	10.47	9.59	9.88	9.90
96	247	5.35	5.20	14.80	14.07	12.74	12.15	12.80	12.65	13.59	
					13.40	13.26	13.15	13.86	13.00	13.70	13.61
96	248	5.16	5.19	13.10	13.18	12.69	12.26	12.91	12.74	12.97	
					13.13	12.92	12.86	13.51	12.67	12.94	13.07
96	249		6.04		9.23	7.94	7.40	8.08	7.77	8.68	
					8.57	8.46	8.40	9.14	8.13	8.80	8.70
96	250		5.69		10.12	9.66	9.26	9.93	9.63	9.96	
					10.07	9.89	9.86	10.53	9.56	9.94	9.98
96	251		5.34		13.20	11.87	11.30	11.95	11.68	12.71	
					12.53	12.39	12.30	13.01	12.04	12.82	12.89

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
96	252		5.16		13.35	12.85	12.43	13.08	12.82	13.14	
					13.30	13.08	13.03	13.68	12.75	13.11	13.27
96	253		4.83		16.63	15.27	14.67	15.30	15.09	16.18	
					15.96	15.78	15.67	16.36	15.45	16.30	16.59
96	254		4.57		17.60	17.06	16.61	17.22	17.06	17.32	
					17.56	17.30	17.21	17.82	16.99	17.29	17.64
97	243		7.15		4.34	3.53	2.86	3.60	3.33	3.59	
					3.77	3.70	3.84	4.57	3.56	3.64	3.83
97	244		7.11		4.73	3.46	3.01	3.74	3.46	4.08	
					4.06	3.97	4.01	4.80	3.81	4.20	3.99
97	245	6.46	6.89	9.20	5.40	4.58	3.90	4.63	4.33	4.65	
					4.83	4.75	4.88	5.60	4.55	4.71	4.89
97	246		6.69		6.53	5.24	4.78	5.49	5.18	5.91	
					5.86	5.75	5.78	6.55	5.54	6.02	5.85
97	247	5.89	6.38	11.00	7.77	6.91	6.22	6.92	6.61	7.03	
					7.19	7.08	7.21	7.90	6.84	7.08	7.28
97	248		5.82		10.91	9.56	9.08	9.74	9.47	10.33	
					10.24	10.08	10.08	10.80	9.83	10.45	10.37
97	249	5.53	5.73	12.40	11.14	10.24	9.53	10.19	9.91	10.41	
					10.56	10.41	10.52	11.16	10.13	10.47	10.71
97	250		6.51		7.34	6.03	5.58	6.28	5.89	6.73	
					6.68	6.55	6.58	7.34	6.25	6.85	6.80
97	251		6.12		9.05	8.17	7.48	8.16	7.79	8.31	
					8.47	8.34	8.46	9.14	8.01	8.37	8.59
97	252		5.82		10.90	9.54	9.07	9.73	9.37	10.32	
					10.23	10.06	10.07	10.79	9.72	10.44	10.53
98	242	7.52	7.63	2.40	2.08	1.66	1.44	2.22	1.94	2.01	
					2.04	1.89	2.04	2.82	1.87	1.99	2.01
98	243	7.40	7.81	3.80	2.39	1.14	0.76	1.55	1.24	1.70	
					1.72	1.65	1.76	2.61	1.60	1.82	1.65
98	245	7.26	7.67	3.90	2.92	1.66	1.28	2.07	1.72	2.24	
					2.26	2.17	2.28	3.13	2.07	2.36	2.22
98	246	6.86	7.06	5.20	4.32	3.86	3.64	4.38	4.03	4.20	
					4.27	4.09	4.24	4.98	3.96	4.17	4.20
98	247		7.34		4.19	2.90	2.53	3.29	2.90	3.52	
					3.52	3.42	3.53	4.35	3.26	3.64	3.52
98	248	6.37	6.61	7.50	6.30	5.81	5.59	6.30	5.93	6.14	
					6.26	6.04	6.19	6.90	5.86	6.12	6.16
98	249	6.29	6.82	11.40	6.39	5.06	4.68	5.41	5.00	5.73	
					5.72	5.58	5.68	6.47	5.36	5.85	5.79
98	250	6.13	6.10	8.70	8.86	8.33	8.10	8.76	8.41	8.64	
					8.82	8.56	8.70	9.36	8.34	8.62	8.71
98	251	6.18	6.64	10.90	7.18	5.85	5.46	6.18	5.74	6.54	
					6.52	6.36	6.47	7.24	6.10	6.65	6.67
98	252	6.22	6.59	8.00	6.41	5.91	5.69	6.40	5.95	6.25	
					6.37	6.15	6.30	7.00	5.88	6.22	6.28

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
98	253	6.13	6.04	8.70	10.15	8.76	8.38	9.04	8.62	9.53	
					9.48	9.28	9.38	10.10	8.98	9.64	9.80
98	254	5.93	6.03	9.30	9.19	8.65	8.42	9.08	8.64	8.97	
					9.15	8.88	9.02	9.68	8.57	8.94	9.06
98	255		5.76		11.70	10.29	9.90	10.53	10.11	11.09	
					11.03	10.80	10.90	11.59	10.47	11.20	11.51
98	256		5.43		12.71	12.11	11.87	12.47	12.09	12.40	
					12.66	12.34	12.47	13.07	12.02	12.38	12.62
99	245	7.86	7.78	2.40	2.65	1.83	1.30	2.11	1.72	1.85	
					2.08	2.00	2.28	3.08	1.95	1.91	2.18
99	246	7.81	7.69	3.70	3.21	1.92	1.61	2.41	2.01	2.51	
					2.54	2.43	2.61	3.47	2.37	2.63	2.52
99	247	7.44	7.52	3.60	3.64	2.79	2.27	3.06	2.63	2.84	
					3.06	2.96	3.25	4.03	2.86	2.89	3.16
99	248	7.16	7.34	5.70	4.60	3.28	2.98	3.75	3.31	3.91	
					3.93	3.80	3.98	4.81	3.67	4.02	3.96
99	249	6.87	7.06	5.80	5.50	4.62	4.09	4.84	4.39	4.69	
					4.92	4.79	5.07	5.81	4.62	4.75	5.01
99	250		6.57		7.94	6.56	6.26	6.96	6.53	7.27	
					7.27	7.08	7.26	8.02	6.89	7.38	7.39
99	251	6.60	6.56	7.50	7.78	6.85	6.33	7.03	6.58	6.97	
					7.20	7.02	7.31	8.00	6.81	7.03	7.30
99	252	6.74	7.47	7.70	4.06	2.75	2.45	3.23	2.70	3.37	
					3.39	3.26	3.45	4.29	3.06	3.48	3.55
99	253	6.74	7.07	6.30	5.47	4.58	4.06	4.81	4.28	4.67	
					4.90	4.75	5.05	5.79	4.51	4.72	4.99
99	254		6.65		7.56	6.18	5.89	6.59	6.07	6.89	
					6.90	6.70	6.89	7.65	6.43	7.00	7.18
99	255	6.44	6.53	7.70	7.91	6.98	6.46	7.15	6.62	7.11	
					7.34	7.15	7.44	8.13	6.85	7.16	7.45
100	244		8.70		−0.93	−1.32	−1.40	−0.49	−0.90	−0.94	
					−0.97	−1.08	−0.80	0.11	−0.97	−0.97	−0.83
100	246	8.38	8.35	0.10	0.24	−0.18	−0.26	0.62	0.17	0.20	
					0.20	0.06	0.34	1.22	0.10	0.17	0.28
100	247	8.21	7.81	2.10	3.21	1.85	1.61	2.44	1.98	2.44	
					2.48	2.36	2.61	3.50	2.33	2.55	2.49
100	249	7.70	7.53	2.60	4.26	2.87	2.64	3.44	2.94	3.49	
					3.53	3.39	3.64	4.50	3.30	3.60	3.58
100	250	7.55	7.62	3.20	2.86	2.39	2.32	3.12	2.60	2.74	
					2.82	2.62	2.92	3.72	2.53	2.72	2.81
100	251	7.43	6.77	6.10	7.51	6.06	5.83	6.54	6.06	6.75	
					6.78	6.57	6.83	7.60	6.42	6.86	6.91
100	252	7.15	7.20	5.00	4.54	4.02	3.96	4.72	4.18	4.37	
					4.49	4.25	4.56	5.32	4.11	4.35	4.45
100	253	7.20	7.46	6.70	4.54	3.14	2.91	3.70	3.12	3.77	
					3.81	3.65	3.92	4.76	3.48	3.88	4.00

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
100	254	7.31	7.64	4.10	2.78	2.30	2.24	3.05	2.44	2.67	
					2.74	2.53	2.84	3.65	2.37	2.64	2.74
100	255	7.23	7.68	4.90	3.68	2.29	2.07	2.88	2.25	2.91	
					2.95	2.81	3.07	3.94	2.61	3.02	3.22
100	256	7.03	7.12	5.10	4.90	4.37	4.32	5.07	4.44	4.72	
					4.86	4.60	4.92	5.67	4.38	4.70	4.82
100	258		6.58		7.33	6.75	6.70	7.39	6.77	7.09	
					7.29	6.98	7.31	7.99	6.70	7.06	7.23
100	260		6.18		9.34	8.72	8.68	9.31	8.70	9.04	
					9.30	8.95	9.28	9.91	8.63	9.02	9.25
101	249		8.43		1.05	0.24	−0.15	0.75	0.20	0.24	
					0.48	0.41	0.83	1.73	0.43	0.30	0.65
101	250	8.25	8.27	3.10	1.92	0.58	0.41	1.30	0.72	1.14	
					1.19	1.09	1.41	2.36	1.08	1.26	1.30
101	251		7.92		2.86	2.00	1.62	2.47	1.88	2.03	
					2.28	2.17	2.61	3.44	2.11	2.09	2.42
101	252		7.44		5.02	3.60	3.45	4.24	3.66	4.23	
					4.29	4.11	4.45	5.30	4.01	4.35	4.44
101	253		7.37		5.02	4.10	3.74	4.51	3.91	4.17	
					4.44	4.27	4.72	5.49	4.14	4.23	4.55
101	254		8.26		1.93	0.57	0.42	1.30	0.64	1.14	
					1.20	1.09	1.42	2.36	1.00	1.26	1.44
101	255		7.78		3.39	2.51	2.14	2.97	2.30	2.56	
					2.81	2.68	3.13	3.95	2.53	2.62	2.94
101	256		7.30		5.60	4.16	4.03	4.79	4.13	4.82	
					4.88	4.68	5.03	5.85	4.49	4.94	5.21
102	246		9.77		−3.45	−3.78	−3.74	−2.68	−3.20	−3.38	
					−3.50	−3.55	−3.14	−2.08	−3.26	−3.41	−3.13
102	247		9.37		−1.33	−2.53	−2.64	−1.62	−2.17	−2.04	
					−1.99	−2.01	−1.64	−0.56	−1.81	−1.93	−1.85
102	248		9.39		−2.38	−2.73	−2.69	−1.66	−2.23	−2.34	
					−2.42	−2.50	−2.09	−1.06	−2.30	−2.37	−2.13
102	249		9.12		−0.58	−1.80	−1.91	−0.92	−1.51	−1.30	
					−1.25	−1.29	−0.91	0.14	−1.16	−1.18	−1.09
102	250		9.19		−1.80	−2.17	−2.12	−1.12	−1.73	−1.78	
					−1.84	−1.94	−1.52	−0.52	−1.80	−1.81	−1.59
102	251	8.82	8.87	0.00	0.18	−1.06	−1.16	−0.19	−0.83	−0.54	
					−0.48	−0.55	−0.16	0.87	−0.48	−0.42	−0.30
102	252	8.55	8.93	0.50	−1.00	−1.40	−1.34	−0.36	−1.03	−1.01	
					−1.04	−1.17	−0.74	0.24	−1.09	−1.04	−0.84
102	253	8.41	8.08	2.00	2.87	1.55	1.48	2.34	1.67	2.14	
					2.20	2.06	2.48	3.40	2.03	2.26	2.40
102	254	8.24	8.68	1.70	−0.19	−0.61	−0.54	0.40	−0.30	−0.23	
					−0.23	−0.38	0.06	1.00	−0.37	−0.25	−0.07
102	255	8.45	8.95	2.80	−0.05	−1.30	−1.39	−0.41	−1.14	−0.77	
					−0.72	−0.78	−0.39	0.65	−0.78	−0.65	−0.40

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
102	256	8.55	8.32	0.50	1.01	0.56	0.64	1.54	0.80	0.94	
					0.97	0.79	1.24	2.14	0.73	0.91	1.08
102	257	8.46	8.04	2.10	3.01	1.67	1.61	2.47	1.72	2.27	
					2.34	2.19	2.61	3.53	2.07	2.39	2.70
102	258	8.20	7.89		2.57	2.07	2.17	3.01	2.24	2.44	
					2.53	2.30	2.77	3.61	2.17	2.42	2.59
102	259	7.81	7.68	4.10	4.37	3.00	2.94	3.76	2.98	3.63	
					3.70	3.51	3.95	4.82	3.33	3.75	4.16
102	260		7.65		3.47	2.94	3.05	3.86	3.06	3.31	
					3.43	3.18	3.65	4.46	2.99	3.29	3.47
102	262		7.19		5.40	4.82	4.94	5.68	4.87	5.17	
					5.35	5.05	5.54	6.28	4.80	5.15	5.37
102	264		6.25		9.90	9.20	9.37	9.93	9.21	9.53	
					9.86	9.43	9.97	10.53	9.14	9.50	9.85
102	266		7.16		5.53	4.94	5.07	5.80	4.92	5.30	
					5.49	5.17	5.67	6.40	4.85	5.28	5.52
103	254		8.43		1.99	0.69	0.68	1.60	0.86	1.26	
					1.32	1.20	1.69	2.66	1.22	1.37	1.56
103	255		8.38		1.90	1.05	0.83	1.74	0.98	1.07	
					1.32	1.22	1.81	2.71	1.21	1.13	1.51
103	256	8.78	9.27	1.90	−0.71	−1.94	−1.96	−0.93	−1.72	−1.43	
					−1.38	−1.42	−0.96	0.13	−1.37	−1.31	−1.00
103	257		8.87		0.28	−0.53	−0.76	0.21	−0.60	−0.53	
					−0.30	−0.36	0.22	1.19	−0.37	−0.48	−0.06
103	258	8.84	8.40	1.00	2.07	0.76	0.76	1.68	0.85	1.33	
					1.40	1.27	1.76	2.74	1.21	1.45	1.81
103	259	8.58	8.34	0.70	2.07	1.20	0.99	1.90	1.05	1.24	
					1.49	1.37	1.98	2.87	1.28	1.29	1.69
103	260	8.15	8.05	2.50	3.33	1.99	2.01	2.87	2.02	2.59	
					2.67	2.50	3.01	3.93	2.37	2.71	3.17
104	248		9.83		−3.03	−3.35	−3.17	−2.05	−2.71	−2.96	
					−3.08	−3.12	−2.57	−1.45	−2.78	−2.98	−2.64
104	250		10.11		−3.81	−4.11	−3.94	−2.78	−3.48	−3.71	
					−3.86	−3.88	−3.34	−2.18	−3.55	−3.73	−3.38
104	251		9.95		−2.37	−3.53	−3.51	−2.38	−3.10	−3.07	
					−3.04	−3.02	−2.51	−1.32	−2.74	−2.95	−2.74
104	252		9.65		−2.53	−2.87	−2.68	−1.58	−2.33	−2.48	
					−2.57	−2.64	−2.08	−0.98	−2.40	−2.50	−2.19
104	253		9.62		−1.45	−2.64	−2.61	−1.52	−2.29	−2.15	
					−2.12	−2.13	−1.61	−0.46	−1.93	−2.04	−1.81
104	254		9.02		−0.64	−1.04	−0.82	0.19	−0.60	−0.66	
					−0.68	−0.81	−0.22	0.79	−0.67	−0.68	−0.41
104	255		8.74		1.24	−0.03	0.04	1.00	0.20	0.52	
					0.58	0.48	1.04	2.06	0.56	0.64	0.87
104	256		8.31		1.72	1.24	1.50	2.39	1.58	1.61	
					1.68	1.48	2.10	2.99	1.52	1.59	1.84

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
104	257		9.59		−1.37	−2.57	−2.53	−1.44	−2.29	−2.07	
					−2.03	−2.05	−1.53	−0.38	−1.94	−1.95	−1.59
104	258	9.40	8.62		0.64	0.19	0.44	1.38	0.52	0.58	
					0.60	0.43	1.04	1.98	0.45	0.55	0.81
104	259		8.76		1.20	−0.08	0.00	0.97	0.07	0.48	
					0.54	0.43	1.00	2.03	0.43	0.60	1.00
104	260		8.79		0.09	−0.35	−0.11	0.86	−0.05	0.04	
					0.04	−0.12	0.49	1.46	−0.12	0.01	0.27
104	261	8.60	8.36	1.90	2.57	1.24	1.34	2.24	1.32	1.83	
					1.90	1.75	2.34	3.30	1.68	1.95	2.45
104	262		8.04		2.73	2.21	2.48	3.33	2.41	2.58	
					2.69	2.44	3.09	3.93	2.34	2.55	2.82
104	263		7.61		5.38	3.96	4.10	4.87	3.96	4.62	
					4.72	4.48	5.10	5.93	4.32	4.74	5.40
104	264		6.91		7.46	6.79	7.13	7.76	6.91	7.13	
					7.42	7.02	7.73	8.36	6.84	7.10	7.44
104	265		6.55		10.21	8.64	8.85	9.39	8.57	9.41	
					9.54	9.15	9.85	10.45	8.93	9.53	10.50
104	266		5.94		12.57	11.74	12.15	12.54	11.83	12.04	
					12.53	11.97	12.75	13.14	11.76	12.02	12.52
104	268		7.20		6.11	5.47	5.81	6.50	5.52	5.83	
					6.07	5.71	6.41	7.10	5.45	5.81	6.14
104	270		7.05		6.81	6.15	6.49	7.15	6.15	6.50	
					6.77	6.38	7.09	7.75	6.08	6.48	6.84
105	258		9.68		−1.33	−2.52	−2.41	−1.29	−2.21	−2.03	
					−2.00	−2.01	−1.41	−0.23	−1.86	−1.91	−1.51
105	259		9.35		−0.59	−1.36	−1.45	−0.38	−1.33	−1.38	
					−1.17	−1.19	−0.47	0.59	−1.10	−1.32	−0.84
105	260	9.28	8.88	0.40	1.12	−0.16	0.00	0.99	0.03	0.40	
					0.45	0.36	1.01	2.05	0.39	0.52	0.96
105	261	9.07	8.78	0.40	1.21	0.38	0.33	1.30	0.32	0.40	
					0.64	0.55	1.31	2.27	0.55	0.45	0.90
105	262	8.80	8.47	2.10	2.51	1.19	1.38	2.29	1.31	1.78	
					1.85	1.70	2.38	3.35	1.66	1.90	2.44
105	263		8.13		3.50	2.59	2.58	3.43	2.44	2.65	
					2.93	2.76	3.56	4.40	2.67	2.70	3.13
105	264		7.77		5.15	3.73	3.96	4.74	3.76	4.38	
					4.48	4.24	4.96	5.80	4.12	4.50	5.21
105	265		7.45		6.20	5.19	5.22	5.93	4.97	5.29	
					5.62	5.36	6.21	6.91	5.20	5.35	5.79
106	252		10.64		−4.63	−4.87	−4.57	−3.30	−4.13	−4.46	
					−4.68	−4.64	−3.97	−2.70	−4.19	−4.49	−4.03
106	254		9.84		−2.50	−2.82	−2.48	−1.32	−2.21	−2.43	
					−2.55	−2.59	−1.88	−0.72	−2.28	−2.45	−2.06
106	256		9.77		−2.30	−2.63	−2.28	−1.14	−2.07	−2.23	
					−2.35	−2.40	−1.68	−0.54	−2.13	−2.26	−1.88

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
106	257		9.28		0.15	−1.08	−0.86	0.20	−0.75	−0.55	
					−0.52	−0.57	0.14	1.26	−0.39	−0.44	−0.13
106	258		9.27		−0.83	−1.21	−0.83	0.23	−0.74	−0.82	
					−0.87	−0.98	−0.23	0.83	−0.81	−0.85	−0.50
106	259		10.15		−2.36	−3.50	−3.33	−2.12	−3.12	−3.03	
					−3.03	−2.99	−2.33	−1.06	−2.76	−2.91	−2.46
106	260		9.81		−2.41	−2.74	−2.38	−1.23	−2.25	−2.33	
					−2.45	−2.51	−1.78	−0.63	−2.32	−2.36	−1.99
106	261		9.35		−0.06	−1.29	−1.06	0.00	−1.03	−0.76	
					−0.73	−0.78	−0.06	1.06	−0.67	−0.64	−0.15
106	262		9.14		−0.42	−0.82	−0.42	0.61	−0.44	−0.43	
					−0.46	−0.59	0.18	1.21	−0.51	−0.46	−0.12
106	263	9.40	8.91	0.00	1.36	0.08	0.33	1.32	0.26	0.64	
					0.69	0.59	1.33	2.38	0.61	0.76	1.34
106	264		8.46		1.88	1.39	1.84	2.74	1.68	1.77	
					1.84	1.62	2.44	3.34	1.61	1.74	2.08
106	265		8.19		3.85	2.47	2.78	3.63	2.56	3.10	
					3.18	2.99	3.78	4.69	2.92	3.22	3.94
106	266		7.74		4.62	4.02	4.53	5.27	4.23	4.39	
					4.57	4.25	5.13	5.87	4.16	4.36	4.72
106	267		7.15		8.17	6.64	7.04	7.63	6.65	7.36	
					7.51	7.15	8.04	8.69	7.00	7.48	8.48
106	268		7.19		6.99	6.31	6.86	7.47	6.45	6.65	
					6.95	6.54	7.46	8.07	6.38	6.63	7.04
106	269		8.06		4.35	2.95	3.28	4.09	2.95	3.59	
					3.68	3.46	4.28	5.15	3.31	3.71	4.74
106	270		8.26		2.59	2.06	2.53	3.39	2.22	2.45	
					2.55	2.29	3.14	3.99	2.15	2.42	2.77
106	272		8.07		3.33	2.77	3.26	4.08	2.87	3.15	
					3.29	3.00	3.86	4.68	2.81	3.13	3.50
106	274		7.53		5.50	4.86	5.40	6.09	4.90	5.23	
					5.46	5.09	6.00	6.69	4.83	5.21	5.63
106	276		7.35		6.24	5.57	6.13	6.78	5.56	5.94	
					6.20	5.80	6.73	7.38	5.50	5.91	6.37
107	258		9.44		−0.04	−1.25	−0.94	0.14	−0.87	−0.73	
					−0.71	−0.74	0.06	1.20	−0.52	−0.61	−0.27
107	259		9.55		−0.60	−1.35	−1.27	−0.16	−1.20	−1.37	
					−1.18	−1.18	−0.28	0.81	−0.97	−1.31	−0.80
107	260		10.34		−2.60	−3.72	−3.47	−2.22	−3.28	−3.25	
					−3.27	−3.21	−2.47	−1.16	−2.93	−3.13	−2.64
107	261		10.08		−2.11	−2.80	−2.75	−1.55	−2.64	−2.84	
					−2.69	−2.63	−1.77	−0.58	−2.41	−2.79	−2.22
107	262		9.57		−0.42	−1.62	−1.31	−0.21	−1.31	−1.10	
					−1.08	−1.11	−0.31	0.85	−0.95	−0.98	−0.45
107	263		9.45		−0.30	−1.07	−0.97	0.11	−1.01	−1.07	
					−0.88	−0.90	0.01	1.09	−0.78	−1.02	−0.51

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
107	264		9.13		0.95	−0.31	0.03	1.06	−0.08	0.25	
					0.29	0.21	1.03	2.12	0.28	0.37	0.99
107	265		8.77		1.88	1.03	1.18	2.13	0.99	1.07	
					1.31	1.20	2.16	3.10	1.22	1.12	1.60
107	266		8.40		3.43	2.08	2.47	3.34	2.21	2.69	
					2.76	2.59	3.48	4.40	2.56	2.81	3.57
107	267		8.06		4.48	3.53	3.74	4.52	3.40	3.60	
					3.90	3.70	4.72	5.50	3.63	3.66	4.12
107	268		7.34		7.72	6.20	6.70	7.29	6.24	6.91	
					7.05	6.71	7.70	8.35	6.60	7.03	8.06
107	269		7.36		7.36	6.29	6.57	7.18	6.09	6.42	
					6.78	6.46	7.55	8.15	6.32	6.48	6.96
107	270		8.21		4.15	2.76	3.18	4.01	2.80	3.40	
					3.49	3.28	4.18	5.07	3.16	3.52	4.59
107	271		8.30		3.56	2.64	2.83	3.68	2.44	2.71	
					2.98	2.81	3.81	4.65	2.67	2.76	3.25
108	258		10.49		−3.74	−3.98	−3.49	−2.21	−3.28	−3.57	
					−3.78	−3.75	−2.89	−1.61	−3.35	−3.60	−3.11
108	260		10.08		−2.61	−2.90	−2.38	−1.17	−2.29	−2.49	
					−2.65	−2.67	−1.78	−0.57	−2.35	−2.52	−2.07
108	261		10.84		−3.62	−4.68	−4.37	−3.03	−4.16	−4.23	
					−4.29	−4.16	−3.37	−1.97	−3.80	−4.11	−3.56
108	262		10.54		−3.86	−4.10	−3.61	−2.32	−3.48	−3.68	
					−3.90	−3.87	−3.01	−1.72	−3.54	−3.71	−3.23
108	263		10.04		−1.51	−2.66	−2.29	−1.09	−2.27	−2.16	
					−2.18	−2.14	−1.29	−0.03	−1.91	−2.04	−1.46
108	264		9.84		−1.95	−2.27	−1.73	−0.57	−1.76	−1.87	
					−1.99	−2.04	−1.13	0.03	−1.83	−1.89	−1.46
108	265		9.56		−0.09	−1.29	−0.89	0.21	−1.00	−0.76	
					−0.76	−0.78	0.11	1.27	−0.64	−0.64	0.02
108	266		9.07		0.45	0.03	0.64	1.63	0.42	0.42	
					0.41	0.26	1.24	2.23	0.35	0.39	0.80
108	267		8.86		2.16	0.86	1.32	2.27	1.05	1.44	
					1.49	1.37	2.33	3.33	1.41	1.56	2.35
108	268		8.56		2.20	1.70	2.36	3.24	2.01	2.08	
					2.16	1.93	2.96	3.84	1.95	2.06	2.46
108	269		7.82		6.01	4.56	5.13	5.81	4.65	5.23	
					5.35	5.07	6.13	6.87	5.00	5.35	6.36
108	270		8.76		1.47	1.00	1.64	2.57	1.29	1.39	
					1.43	1.23	2.24	3.17	1.22	1.36	1.77
108	271		8.76		2.50	1.18	1.67	2.59	1.29	1.78	
					1.84	1.70	2.67	3.65	1.65	1.90	2.98
108	272		8.93		0.91	0.46	1.09	2.06	0.72	0.86	
					0.87	0.69	1.69	2.66	0.65	0.83	1.24
108	274		9.33		−0.39	−0.79	−0.19	0.86	−0.54	−0.39	
					−0.43	−0.56	0.41	1.46	−0.60	−0.41	0.01

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
108	276		8.42		2.70	2.17	2.86	3.70	2.32	2.56	
					2.66	2.40	3.46	4.30	2.25	2.54	2.98
108	278		7.91		4.64	4.03	4.76	5.48	4.10	4.41	
					4.60	4.26	5.36	6.08	4.03	4.38	4.86
108	280		7.67		5.65	5.00	5.76	6.41	5.02	5.37	
					5.61	5.23	6.36	7.01	4.95	5.34	5.87
109	262		12.15		−6.43	−7.34	−7.03	−5.46	−6.62	−6.95	
					−7.10	−6.83	−6.03	−4.40	−6.26	−6.84	−6.12
109	263		11.91		−6.15	−6.63	−6.53	−4.99	−6.18	−6.74	
					−6.73	−6.46	−5.54	−4.02	−5.95	−6.68	−5.88
109	264		11.50		−4.98	−5.96	−5.60	−4.14	−5.36	−5.53	
					−5.65	−5.44	−4.60	−3.08	−5.01	−5.42	−4.70
109	265		11.37		−4.90	−5.44	−5.30	−3.85	−5.10	−5.52	
					−5.48	−5.27	−4.31	−2.88	−4.87	−5.46	−4.74
109	266		11.06		−3.92	−4.95	−4.56	−3.17	−4.45	−4.50	
					−4.59	−4.43	−3.56	−2.11	−4.09	−4.38	−3.62
109	267		12.72		−7.85	−8.26	−8.20	−6.54	−7.76	−8.39	
					−8.42	−8.09	−7.22	−5.57	−7.53	−8.33	−7.42
109	268		10.38		−2.18	−3.28	−2.84	−1.58	−2.91	−2.79	
					−2.85	−2.77	−1.84	−0.52	−2.55	−2.67	−1.85
109	269		10.06		−1.51	−2.20	−1.95	−0.75	−2.10	−2.22	
					−2.08	−2.03	−0.96	0.22	−1.87	−2.16	−1.58
109	270		9.35		0.86	−0.38	0.16	1.20	−0.15	0.18	
					0.19	0.14	1.16	2.26	0.20	0.30	1.25
109	271		9.41		0.43	−0.34	−0.04	1.02	−0.35	−0.33	
					−0.15	−0.17	0.95	2.00	−0.13	−0.27	0.27
109	272		10.18		−1.63	−2.76	−2.30	−1.07	−2.49	−2.25	
					−2.29	−2.25	−1.30	−0.01	−2.13	−2.13	−1.07
110	262		11.87		−6.59	−6.66	−6.10	−4.55	−5.78	−6.23	
					−6.64	−6.43	−5.49	−3.95	−5.85	−6.26	−5.60
110	263		12.54		−7.04	−7.89	−7.53	−5.87	−7.09	−7.52	
					−7.71	−7.38	−6.53	−4.81	−6.73	−7.40	−6.62
110	264		12.24		−7.41	−7.44	−6.90	−5.29	−6.54	−7.00	
					−7.45	−7.21	−6.30	−4.69	−6.61	−7.03	−6.34
110	265		11.96		−5.80	−6.71	−6.30	−4.74	−6.03	−6.31	
					−6.47	−6.20	−5.30	−3.68	−5.67	−6.19	−5.41
110	266		11.73		−6.29	−6.38	−5.80	−4.27	−5.59	−5.95	
					−6.34	−6.15	−5.20	−3.67	−5.66	−5.97	−5.35
110	267		11.58		−4.93	−5.88	−5.45	−3.95	−5.30	−5.46	
					−5.60	−5.37	−4.45	−2.89	−4.94	−5.34	−4.51
110	268		11.14		−4.90	−5.05	−4.42	−3.00	−4.38	−4.63	
					−4.94	−4.82	−3.82	−2.40	−4.45	−4.65	−4.09
110	269		10.98		−3.48	−4.50	−4.01	−2.63	−4.03	−4.04	
					−4.14	−3.98	−3.01	−1.57	−3.67	−3.92	−3.04
110	270		10.99		−4.52	−4.70	−4.05	−2.66	−4.09	−4.27	
					−4.57	−4.47	−3.45	−2.06	−4.15	−4.30	−3.75

Table 2. cont. Tab. 2 c.d.

Z	A	Q^{exp}	Q^{th}	EXP	VS	TN	FR	WA	HO	KM	PI
—	—	MeV	MeV	—	—	—	—	—	—	—	—
110	271		9.99		−0.82	−1.96	−1.38	−0.21	−1.65	−1.44	
					−1.48	−1.45	−0.38	0.85	−1.29	−1.32	−0.35
110	272		10.36		−2.85	−3.11	−2.40	−1.14	−2.61	−2.69	
					−2.90	−2.88	−1.80	−0.54	−2.68	−2.71	−2.21
110	273		10.87		−3.20	−4.24	−3.73	−2.37	−3.86	−3.76	
					−3.86	−3.72	−2.73	−1.31	−3.50	−3.64	−2.54
110	274		10.80		−4.03	−4.24	−3.57	−2.22	−3.73	−3.81	
					−4.08	−4.00	−2.97	−1.62	−3.79	−3.83	−3.30
110	275		10.69		−2.74	−3.80	−3.28	−1.96	−3.48	−3.32	
					−3.41	−3.29	−2.28	−0.90	−3.13	−3.20	−1.98
110	276		11.27		−5.21	−5.36	−4.73	−3.29	−4.83	−4.92	
					−5.25	−5.13	−4.13	−2.69	−4.89	−4.95	−4.39
110	278		10.25		−2.55	−2.82	−2.10	−0.86	−2.45	−2.40	
					−2.59	−2.59	−1.50	−0.26	−2.52	−2.42	−1.92
110	280		10.22		−2.47	−2.76	−2.03	−0.80	−2.43	−2.33	
					−2.52	−2.52	−1.42	−0.20	−2.50	−2.35	−1.85
110	282		9.44		−0.16	−0.55	0.26	1.31	−0.34	−0.13	
					−0.20	−0.31	0.86	1.91	−0.41	−0.16	0.35
110	284		11.14		−4.90	−5.07	−4.42	−3.00	−4.71	−4.62	
					−4.94	−4.84	−3.82	−2.40	−4.77	−4.65	−4.10
110	286		10.60		−3.51	−3.75	−3.05	−1.74	−3.49	−3.31	
					−3.55	−3.52	−2.45	−1.14	−3.56	−3.33	−2.81
111	267		11.95		−5.79	−6.23	−5.96	−4.38	−5.77	−6.33	
					−6.37	−6.06	−4.97	−3.40	−5.54	−6.27	−5.47
111	268		11.62		−4.80	−5.73	−5.21	−3.69	−5.12	−5.30	
					−5.47	−5.22	−4.21	−2.63	−4.76	−5.19	−4.34
111	269		11.26		−4.16	−4.68	−4.34	−2.89	−4.35	−4.74	
					−4.73	−4.51	−3.36	−1.92	−4.12	−4.68	−3.98
111	270		10.92		−3.08	−4.09	−3.50	−2.13	−3.61	−3.62	
					−3.75	−3.58	−2.50	−1.07	−3.25	−3.50	−2.60
111	271		8.58		3.89	2.99	3.62	4.40	3.01	3.06	
					3.31	3.16	4.60	5.37	3.24	3.11	3.58
111	272		9.85		−0.12	−1.27	−0.57	0.56	−0.95	−0.73	
					−0.78	−0.76	0.43	1.62	−0.59	−0.61	0.39
111	273		9.92		−0.55	−1.24	−0.77	0.38	−1.15	−1.24	
					−1.12	−1.07	0.22	1.35	−0.92	−1.19	−0.61
111	274		10.65		−2.39	−3.44	−2.82	−1.50	−3.06	−2.95	
					−3.05	−2.92	−1.82	−0.44	−2.71	−2.83	−1.69
111	275		10.79		−2.97	−3.55	−3.16	−1.82	−3.40	−3.59	
					−3.55	−3.38	−2.18	−0.84	−3.17	−3.53	−2.87
111	276		10.53		−2.05	−3.12	−2.49	−1.20	−2.80	−2.62	
					−2.72	−2.61	−1.49	−0.14	−2.45	−2.50	−1.23