Systematical analysis of (n,2n) reaction cross sections for 14-15 MeV neutrons

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Fast neutron induced nuclear reaction cross section data are necessary for both nuclear energy technology and the understanding of fundamental nuclear physics problems. The information of (n,2n) cross sections is quite essential in nuclear technology as a significant portion of the fission neutron spectrum lies above the threshold of (n,2n) reaction for most of the reactor materials. These cross section data are required in shielding and breeding calculations. Radioactive nuclides produced in the reactor usually have short half-life. So, direct measurement of their neutron cross sections is difficult. Therefore, model formulae are important to predict these cross sections theoretically.

In this work, in the framework of the statistical model we deduced some theoretical formulae for the (n,2n) cross section using the evaporation model, constant nuclear temperature approximation and Weizsäker's formula for binding energy. The model formulae were utilized for systematical analysis of known experimental data of the (n,2n) cross sections at 14 - 15 MeV energy.

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INTRODUCTION

Fast neutron induced nuclear reaction cross section data are necessary for both nuclear energy technology and the understanding of fundamental nuclear physics problems. The information of (n,2n) cross sections is required in shielding and breeding calculations, because a significant portion of the fission neutron spectrum lies above the threshold of (n,2n) reaction for most of the reactor materials. Furthermore, the application of the fast neutron induced nuclear reaction cross section data have been increasing in the fields of biomedical applications, accelerator driven transmutation, material irradiation experiments concerning research and development for fusion reactor technology.

Radioactive nuclides produced in the reactor usually have short half-life. So direct measurement of their neutron cross sections is difficult. Therefore, model formulae are important to predict these cross sections theoretically.

Systematics of (n,2n) reaction cross sections for fast neutrons have been studied by many authors [1-6]. Konobeyev *et al.* have derived some formula for the (n,2n) reaction cross section estimation at the energy of 14.5 MeV employing the pre-equilibrium and evaporation models [3]. Luo *et al.* [4] and Habbani *et al.* [5] carried out systematical analysis of (n,2n) reaction cross sections based on the statistical model.

In this work, in the framework of the statistical model we deduced some theoretical formulae for the (n,2n) cross section using the evaporation model, constant nuclear temperature approximation and Weizsäker's formula for binding energy. Known experimental data of the (n,2n) cross sections at 14 - 15 MeV neutrons are analyzed with the help of the obtained formulae.

STATISTICAL MODEL FORMULAE

In the framework of the statistical model based on the Bohr's assumption of a compound mechanism the cross section formula for (*n*,*x*) reaction is expressed as [7]:

$$\sigma(n,x)=\sigma_c(n)\frac{2S_x+1}{2S_n+1}\frac{M_x}{M_n}e^{\frac{Q_{n,x}-V_x}{\Theta}}\left\{\frac{1-\frac{W_{n,x}}{\Theta}e^{-\frac{W_{n,x}}{\Theta}}-e^{-\frac{W_{n,x}}{\Theta}}}{1-\frac{E_n}{\Theta}e^{-\frac{E_n}{\Theta}}-e^{-\frac{E_n}{\Theta}}}\right\}, \tag{1}$$

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where: $\sigma_c(n)$ is the compound nucleus formation cross section; S_n and S_x are the spin of the incident neutron and emitted x particle respectively; M_n and M_x are the masses of the neutron and x particle respectively; $Q_{n,x}$ is the reaction energy; V_x is the Coulomb barrier for x particle; Θ is the thermodynamic temperature; E_n is the incident neutron energy; $W_{n,x} = E_n + Q_{n,x} - V_x$.

According to our evaluations, term in the curly brackets of the formula (1) approximately equals to 1 for the fast neutron induced (n,2n) reaction cross sections except a few very light nuclei. Then, from the formula (1) can be obtained following formula, which is similar to Cuzzocrea's *et al.* [8] and Ericson's [9] formulas:

$$\sigma(n,2n) = \sigma_c(n)\frac{2S_{2n}+1}{2S_n+1}\frac{M_{2n}}{M_n}e^{\frac{Q_{n,2n}-V_{2n}}{\Theta}}. \qquad (2)$$

The compound nucleus formation cross section:

$$\sigma_c(n) = \pi(R+\bar{\lambda}_n)^2, \qquad (3)$$

where: R is the radius of the target nucleus; $\bar{\lambda}_n$ is the wavelength of the incident neutron divided by 2π.

The Coulomb barrier for neutrons $V_{2n} = 0$. So, taking into account the spin and mass of neutrons from the formula (2) we get:

$$\sigma(n,2n) = 4\pi(R+\bar{\lambda}_n)^2 e^{\frac{Q_{n,2n}}{\Theta}}. \qquad (4)$$

Using the Weizsäker's formula for binding energy we can obtain following expressions for the target and residual nuclei:

$$E_i = \alpha A - \beta A^{2/3} - \gamma\frac{Z^2}{A^{1/3}} - \xi\frac{(N-Z)^2}{A} \pm \frac{\delta_i}{A^{3/4}} \qquad (5)$$

and

$$E_f = \alpha(A-1) - \beta(A-1)^{2/3} - \gamma\frac{Z^2}{(A-1)^{1/3}} - \\ -\xi\frac{(N-1-Z)^2}{A-1} \pm \frac{\delta_f}{(A-1)^{3/4}}, \qquad (6)$$

Then, we get the (n,2n) reaction energy $Q_{n,2n}$ as following:

$$Q_{n,2n} = -\alpha - \beta\left\{(A-1)^{2/3} - A^{2/3}\right\} - \gamma\left\{\frac{Z^2}{(A-1)^{1/3}} - \frac{Z^2}{A^{1/3}}\right\} - \\ -\xi\left\{\frac{(N-1-Z)^2}{A-1} - \frac{(N-Z)^2}{A}\right\} \pm \frac{\delta_f}{(A-1)^{3/4}} \mp \frac{\delta_i}{A^{3/4}}. \qquad (7)$$

where: α = 15.7 MeV; β = 17.8 MeV;
γ = 0.71 MeV; ξ = 23.7 MeV;
δ_i and δ_f depend on either odd or even number of neutrons and protons $|\delta|$ = 34 MeV or 0.

From (4) and (7) we get the (n,2n) cross section formula:

$$\sigma(n,2n) = 4\pi(R+\bar{\lambda}_n)^2 \exp\left\{\frac{-\alpha - \beta\left((A-1)^{2/3} - A^{2/3}\right) - \gamma\left(\frac{Z^2}{(A-1)^{1/3}} - \frac{Z^2}{A^{1/3}}\right) - \xi\left(1 - \frac{4Z^2}{A(A-1)}\right) \pm \frac{\delta_f}{(A-1)^{3/4}} \mp \frac{\delta_i}{A^{3/4}}}{\Theta}\right\}. \qquad (8)$$

In the case of A >> 1 can be obtain the following formulae for systematical analysis of the (n,2n) cross sections:

$$\frac{\sigma(n,2n)}{\pi(R+\bar{\lambda}_n)^2} = C\exp(-K\frac{Z^2}{A^2}), \qquad (9)$$

where: Z and A are proton and mass numbers of the target nuclei; the parameters K and C are expressed as:

$$K = \frac{4\xi}{\Theta}; \qquad (10)$$

$$C = 4\exp\left\{\frac{-\alpha - \beta\left((A-1)^{2/3} - A^{2/3}\right)}{\Theta} - \\ -\frac{\gamma\left(\frac{Z^2}{(A-1)^{1/3}} - \frac{Z^2}{A^{1/3}}\right) \pm \frac{\delta_f}{(A-1)^{3/4}} \mp \frac{\delta_i}{A^{3/4}} + \xi}{\Theta}\right\}. \qquad (11)$$

The formula (9) is used for systematics of (n,2n) reaction cross sections.

SYSTEMATICS OF (n,2n) REACTION CROSS SECTIONS AND DISCUSSIONS

In this paper the library of neutron cross sections known as EXFOR, IAEA presented in ref. [10] is used. We've analyzed 147 experimental (n,2n) cross section data at the neutron energy of 14 – 15 MeV from EXFOR, which are presented in the Appendix. The dependence of the reduced (n,2n) cross section on the parameter Z^2/A^2 is shown in the Fig. 1. Also, a fitted curve to experimental (n,2n) cross section data is shown in the Fig. 1.

It's seen that the theoretical curve by the statistical model formula (9) is in not good agreement with experimental data points. This fact perhaps shows that the statistical model is not suitable to explain (n,2n) cross sections for 14 – 15 MeV neutrons.

A total cross section for fast neutrons can be approximated as following:

$$\sigma_n^{tot} = \sigma^{tot}(n,2n) + \sigma^{tot}(n,\gamma) + \sigma^{tot}(n,\alpha) + \\ +\sigma^{tot}(n,p) + \sigma^{tot}(n,3n) + \ldots \approx \\ \approx \sigma^{tot}(n,2n) \approx \pi(R+\bar{\lambda}_n)^2. \qquad (12)$$

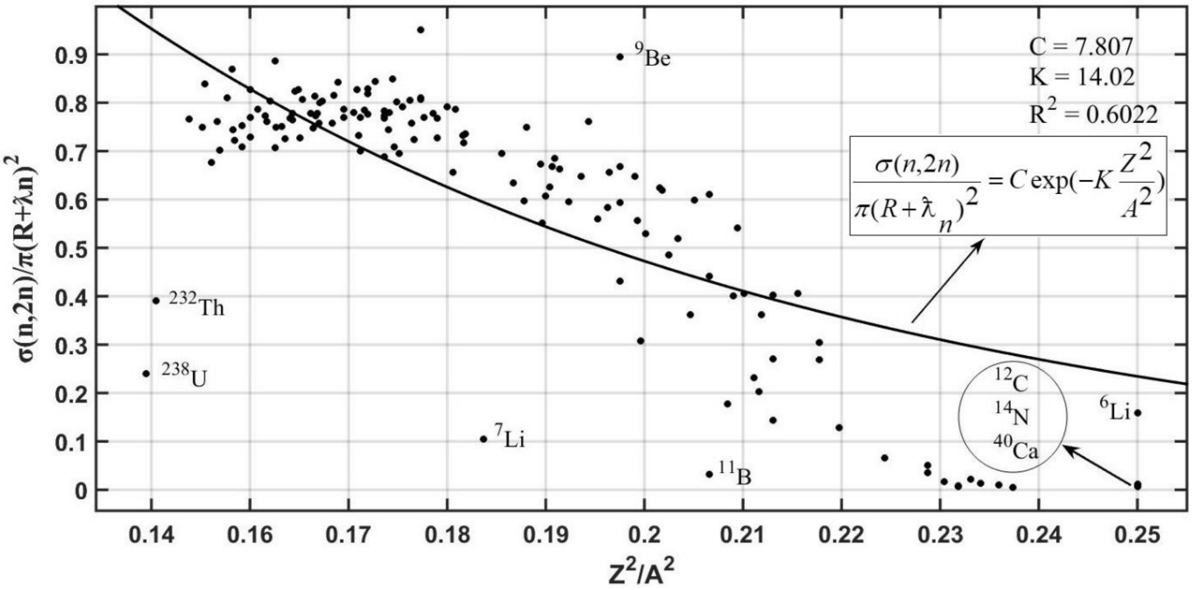

Figure 1. The dependence of the reduced (n,2n) cross sections on parameter Z^2/A^2.

On the other hand, if we take, in addition, into account the pre-equilibrium and direct mechanisms the total (n,2n) cross section can be obtained as follows:

$$\sigma_n^{tot} \approx \sigma^{tot}(n,2n) \approx \pi(R+\bar{\lambda}_n)^2 \approx \\ \approx \sigma^{comp}(n,2n) + \sigma^{pre}(n,2n) + \sigma^{dir}(n,2n), \qquad (13)$$

where: $\sigma^{comp}(n,2n)$ is determined by formula (9).

The sum of the cross sections of pre-equilibrium and direct mechanisms are taken as the non-statistical:

$$\sigma^{nonstat}(n,2n) = \sigma^{pre}(n,2n) + \sigma^{dir}(n,2n). \qquad (14)$$

Then, the non-statistical (n,2n) cross section is determined as:

$$\sigma^{nonstat}(n,2n) = \sigma^{tot}(n,2n) - \sigma^{comp}(n,2n) = \\ = \pi(R+\bar{\lambda}_n)^2 - C\pi(R+\bar{\lambda}_n)^2 \exp(-K\frac{Z^2}{A^2}) = \\ = \pi(R+\bar{\lambda}_n)^2\left(1 - C\exp(-K\frac{Z^2}{A^2})\right). \qquad (15)$$

Then, the reduced (n,2n) cross section is expressed as:

$$\frac{\sigma^{nonstat}(n,2n)}{\pi(R+\bar{\lambda}_n)^2} = \left(1 - C\exp(-K\frac{Z^2}{A^2})\right). \qquad (16)$$

The dependence of the reduced (n,2n) cross sections on the parameter Z^2/A^2 is given in Fig. 2. Formula (16) is used for fitting to the experimental (n,2n) cross section data. The very heavy nuclei such as ^{238}U, ^{232}Th and very light nuclei ^{6,7}Li, ^{9}Be, ^{11}B, ^{12}C, ^{14}N are excluded from the consideration. Also, double magic nucleus ^{40}Ca is not considered.

It's seen from Fig. 2, that the theoretical line is in satisfactorily agreement with the experimental data. Also, in Fig. 2 experimental errors of the cross sections for some isotopes are given, as example.

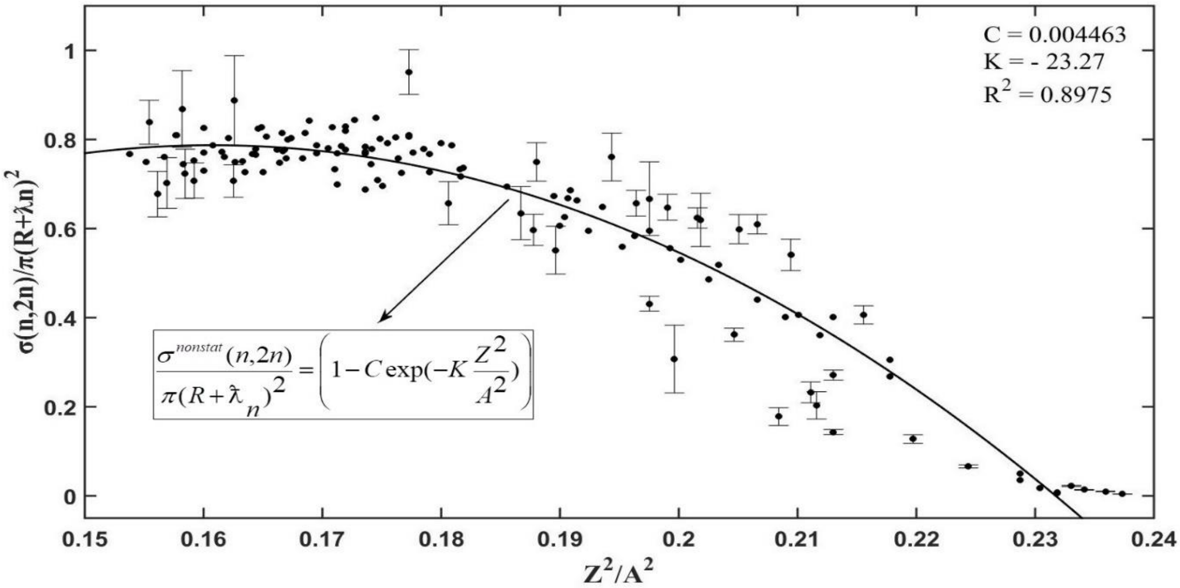

Figure 2. The dependence of the reduced (n,2n) cross sections on parameter Z^2/A^2.

CONCLUSIONS

1. In the framework of the statistical model a theoretical formula for the (n,2n) reaction cross section was deduced. In addition, a non-statistical share of the total neutron cross section was obtained.
2. Known experimental data of the (n,2n) cross sections for 14 – 15 MeV neutrons were analyzed using the obtained formulae. It was shown that the non-statistical share of the total cross section is in agreement with experimental data.

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APPENDIX

Table 1. Experimental data for (n,2n) reaction cross sections at 14-15 MeV energy [10] used in the systematics.

Target nuclei	A	N	Z	E, (MeV)	σ(n,2n) (mb)	Δσ(n,2n) (mb)	Authors
Li	6	3	3	14.06	78.1	4.1	Mather *et al*. (1969)
Li	7	4	3	14.06	49.7	3.2	Mather *et al*. (1969)
Be	9	5	4	14.1	478	14	Takahashi *et al*. (1987)
B	11	6	5	14.06	19	4	Mather *et al*. (1969)
C	12	6	6	14.1	6	6	Ashby *et al*. (1958)
C	13	7	6	14.28	255	25	Frehaut *et al*. (1978)
N	14	7	7	14.64	7.28	0.29	Sakane *et al*. (2001)
F	19	10	9	14.69	50.4	2.7	Ikeda *et al*. (1988)
Na	23	12	11	14.87	41.7	0.9	Hanlin *et al*. (1992)
Al	27	14	13	14.09	7.8	0.5	Wallner *et al*. (2003)
P	31	16	15	14.64	13.2	0.71	Sakane *et al*. (2001)
Cl	35	18	17	14.57	10.28	0.8	Molla *et al*. (1997)
K	39	20	19	14.66	4.55	0.25	Filatenkov (2016)
Ca	40	20	20	14.69	8	2	Braun *et al*. (1968)
Ca	48	28	20	14.7	850	35	Anders *et al*. (1985)
Sc	45	24	21	14.8	320	24	J.Luo *et al*. (2013)
Ti	46	24	22	14.72	42	2.3	Ikeda *et al*. (1998)
V	50	27	23	14.3	258	39	Greenwood *et al*. (1992)
Cr	50	26	24	14.6	21.2	1.2	Ribansky *et al*. (1985)
Cr	52	28	24	14.47	351	14.49	Mannhart *et al*. (2007)
Mn	55	30	25	14.58	812.9	28.9	Hanlin *et al*. (1980)
Fe	54	28	26	14.64	9	1.8	Sakane *et al*. (2001)
Fe	56	30	26	14.82	545.4	27.3	Wallner *et al*. (2011)
Co	59	32	27	14.51	750	49	Molla *et al*. (1994)
Ni	58	30	28	14.32	30.6	1.65	Ikeda *et al*. (1984)
Ni	60	32	28	14.6	426	53	Ming He *et al*. (2015)
Ni	64	36	28	14.8	958	64	Greenwood *et al*. (1992)
Cu	63	34	29	14.33	520	51.25	Mannhart *et al*. (2007)
Cu	65	36	29	14.42	948	42.57	Filatenkov (2016)
Zn	64	34	30	14.5	185	14	Chatterjee *et al*. (1969)
Zn	66	36	30	14.28	652	11.9	Wagner *et al*. (1989)
Ga	69	38	31	14.8	933	90	Luo *et al*. (2012)
Ga	71	40	31	14.1	1030	147	Luo *et al*. (2012)
Ge	70	38	32	14.8	608	92	Molla *et al*. (1983)
Ge	72	40	32	14.74	917	77	Dzysiuk *et al*. (2007)
Ge	76	44	32	14.57	1290	102	Molla *et al*. (1997)
As	75	42	33	14.28	1028	75	Frehaut *et al*. (1980)

Se	74	40	34	14.44	364.99	36.86	Filatenkov (2016)
Se	76	42	34	14.44	844	89.46	Filatenkov (2016)
Se	78	44	34	14.76	978	72	Frehaut *et al.* (1980)
Se	80	46	34	14.76	1074	79	Frehaut *et al.* (1980)
Se	82	48	34	14.44	1363	196.27	Filatenkov (2016)
Br	79	44	35	14.58	950	50.35	Sakane *et al.* (2001)
Br	81	46	35	14.6	1047	98	Strohal *et al.* (1962)
Kr	78	42	36	14	233	9	Bazan (1989)
Kr	80	44	36	14.4	810	60	Kondaiah *et al.* (1968)
Rb	85	48	37	14.7	1140	35	Pepelnik *et al.* (1986)
Rb	87	50	37	14.7	1350	42	Pepelnik *et al.* (1986)
Sr	84	46	38	14.6	609	25	Guozhu He *et al.* (2006)
Sr	86	48	38	14.6	955	57	Guozhu He *et al.* (2006)
Y	88	49	39	14.19	1140	50	Prestwood *et al.* (1984)
Zr	90	50	40	14.7	754	29	Anders *et al.* (1985)
Zr	96	56	40	14.7	1420	81	Anders *et al.* (1985)
Nb	93	52	41	14.3	1360	96	Lychagin *et al.* (1984)
Mo	92	50	42	14.7	190	10	Pepelnik *et al.* (1986)
Mo	94	52	42	14.7	550	136	Greenwood *et al.* (1990)
Mo	100	58	42	14.64	1406	47.24	Filatenkov (2016)
Ru	96	52	44	14.8	735	22	Junhua Luo *et al.* (2007)
Ru	98	54	44	14.1	1151	42	Junhua Luo *et al.* (2007)
Ru	104	60	44	14.09	1464.4	143.65	Bormann (1970)
Rh	103	58	45	14.47	1296	76.72	Filatenkov (2016)
Pd	102	56	46	14.05	980	50.37	Filatenkov (2016)
Pd	110	64	46	14.88	1566	202.01	Filatenkov (2016)
Cd	106	58	48	14.5	1150	63	Kong Xiangzhong *et al.* (1995)
Cd	108	60	48	14.8	1291	160	Goncalves *et al.* (1987)
Cd	110	62	48	14.5	1226	79	Kong Xiangzhong *et al.* (1995)
Cd	114	66	48	14.7	1900	100	Panteleev *et al.* (1996)
Cd	116	68	48	14.19	1418	258.08	Filatenkov (2016)
In	113	64	49	14.6	1491	86	Holub *et al.* (1976)
In	115	66	49	14.8	1469.6	87.9	Junhua Luo *et al.* (2007)
Sn	112	62	50	14.4	1104	43	Betak *et al.* (2005)
Sn	114	64	50	14.64	1190	120	Ikeda *et al.* (1988)
Sn	124	74	50	14.49	1862	212.27	Filatenkov (2016)
Sb	121	70	51	14.2	1599	75	Lakshmana Das *et al.* (1978)
Sb	123	72	51	14.4	1625	163	Ghorai *et al.* (1980)
Te	120	68	52	14.67	1228	72.084	Filatenkov (2016)
Te	122	70	52	14.67	1488	93.744	Filatenkov (2016)
Te	130	78	52	14.67	1779	81.478	Filatenkov (2016)
I	127	74	53	14.7	1655	173	Anders *et al.* (1985)
Xe	124	70	54	14.4	1159	112.8	Kondaiah (1968)
Xe	136	82	54	14.45	1794.1	40.02	Bhatia *et al.* (2013)

Cs	133	78	55	14.2	1605.9	133.67	Nagel (1966)
Ba	130	74	56	14.43	1499	95	Konno *et al.* (1993)
Ba	132	76	56	14.67	1720	120	Konno *et al.* (1993)
Ba	134	78	56	14.5	1556	95	Csikai *et al.* (1991)
Ce	136	78	58	14.7	1625	90	Xiangzhong Kong *et al.* (1997)
Ce	138	80	58	14.8	1612	128	Junhua Luo *et al.* (2015)
Ce	140	82	58	14.45	1766	71	Chuanxin Zhu *et al.* (2011)
Ce	142	84	58	14.66	1760	80	Kasugai *et al.* (1997)
Pr	141	82	59	14.58	1570	188.4	Sakane *et al.* (2001)
Nd	142	82	60	14.6	1764	111	Pu Zhong-Sheng *et al.* (2004)
Nd	144	84	60	14.76	1763	133	Frehaut *et al.* (1980)
Nd	146	86	60	14.76	1937	148	Frehaut *et al.* (1980)
Nd	148	88	60	14.76	1773	137	Frehaut *et al.* (1980)
Nd	150	90	60	14.8	1703	82	Gmuca *et al.* (1983)
Sm	148	86	62	14.76	1835	135	Frehaut *et al.* (1980)
Sm	150	88	62	14.76	1931	143	Frehaut *et al.* (1980)
Sm	152	90	62	14.76	1760	138	Frehaut *et al.* (1980)
Sm	154	92	62	14.7	1905	105	Xiangzhong Kong *et al.* (1998)
Eu	151	88	63	14.28	1753	135	Frehaut *et al.* (1980)
Eu	153	90	63	14.61	1819	71.31	Filatenkov (2016)
Gd	152	88	64	14.8	1896	157	Junhua Luo *et al.* (2010)
Gd	154	90	64	14.8	2001	108	Junhua Luo *et al.* (2010)
Gd	155	91	64	14.28	1864	152	Frehaut *et al.* (1980)
Gd	156	92	64	14.28	1819	140	Frehaut *et al.* (1980)
Gd	157	93	64	14.28	1872	157	Frehaut *et al.* (1980)
Gd	158	94	64	14.28	1856	145	Frehaut *et al.* (1980)
Gd	160	96	64	14.28	1874	152	Frehaut *et al.* (1980)
Tb	159	94	65	14.8	1930	135.1	Prestwood *et al.* (1984)
Dy	156	90	66	14.7	1736	96	Dzysiuk *et al.* (2012)
Dy	158	92	66	14.7	2044	108	Dzysiuk *et al.* (2012)
Ho	165	98	67	14.7	2042	303	Qaim (1974)
Er	162	94	68	14.7	1967	163	Dzysiuk *et al.* (2012)
Er	164	96	68	14.7	2040	430	Dzysiuk *et al.* (2012)
Tm	169	100	69	14.5	1939	29.09	Greenwood (1987)
Yb	168	98	70	14.8	1914	169	Junhua Luo *et al.* (2013)
Yb	170	100	70	14.7	1976	245	Dzysiuk *et al.* (2012)
Yb	176	106	70	14.7	2225	220	Xiangzhong Kong *et al.* (1997)
Lu	175	104	71	14.28	2113	155	Frehaut *et al.* (1980)
Hf	174	102	72	14.2	1968	148	Lakshmana Das *et al.* (1981)
Hf	176	104	72	14.7	2057	148.1	Meadows *et al.* (1996)
Ta	181	108	73	14.28	1957	150	Frehaut *et al.* (1980)
W	182	108	74	14.5	2110	75	Kong Xiangzhong *et al.* (1997)
W	183	109	74	14.28	1910	166	Frehaut *et al.* (1980)

W	184	110	74	14.28	2009	154	Frehaut *et al.* (1980)
W	186	112	74	14.68	1969	257.94	Filatenkov (2016)
Re	185	110	75	14.67	2052	164	Wang Xiuyuan *et al.* (1989)
Os	186	110	76	14.7	2004	120	Bornemisza-Paus (1980)
Os	192	116	76	14.66	2050	190	Konno *et al.* (1993)
Ir	191	114	77	14.47	1902	97.76	Filatenkov (2016)
Ir	193	116	77	14.43	2040	100	Konno *et al.* (1993)
Pt	190	112	78	14.4	2187	164	Luo Jun-Hua *et al.* (2005)
Pt	192	114	78	14.47	1964	259.25	Filatenkov (2016)
Pt	198	120	78	14.8	2054	205	Yang Weifan *et al.* (1984)
Au	197	118	79	14.65	2154	32.31	Greenwood (1987)
Hg	196	116	80	14.68	2220	170	Kasugai *et al.* (2001)
Hg	198	118	80	14.68	2060	130	Kasugai *et al.* (2001)
Hg	204	124	80	14.68	2140	100	Kasugai *et al.* (2001)
Tl	203	122	81	14.7	1970	110	Kiraly *et al.* (2001)
Tl	205	124	81	14.76	1895	143	Frehaut *et al.* (1980)
Pb	204	122	82	14.5	2161	172.45	Filatenkov (2016)
Pb	206	124	82	14.76	2028	155	Frehaut *et al.* (1980)
Pb	207	125	82	14.76	1976	161	Frehaut *et al.* (1980)
Pb	208	126	82	14.1	2380	140	Simakov *et al.* (1992)
Bi	209	126	83	14.74	2293	371.47	Filatenkov (2016)
Th	232	142	90	14.7	1177	78.86	Chatani *et al.* (1991)
U	238	146	92	14.62	732	58	Raics *et al.* (1990)