Pramana – J. Phys. (2023) 97:12
https://doi.org/10.1007/s12043-022-02485-x

An accurate empirical formula for the average total kinetic energy released in fission

H C MANJUNATHA[1,*], N SOWMYA[1,*], K N SRIDHAR[2], L SEENAPPA[1] and
P S DAMODARA GUPTA[1]

[1]Department of Physics, Government College for Women, Kolar 563 101, India
[2]Department of Physics, Government First Grade College, Kolar 563 101, India
*Corresponding authors. E-mail: manjunathhc@rediffmail.com; sowmyaprakash8@gmail.com

MS received 9 March 2022; revised 7 August 2022; accepted 23 August 2022

Abstract. The empirical formulae for an average total kinetic energy released during the symmetric and asymmetric fission has been estimated by considering the recently available experimental data. An empirical formulae is deduced by the systematic variation of $\langle E_K \rangle$ with $Z^2/A^{1/3}$. The least-square analysis of symmetric fission yields $\langle E_K \rangle = 0.12014(Z^2/A^{1/3}) + 5.99$ MeV in the atomic number range $23 \le Z \le 120$ and mass number range $46 \le A \le 302$, whereas asymmetric fission yields $\langle E_K \rangle = 0.1367(Z^2/A^{1/3}) - 18.94$ MeV in the atomic number range $78 \le Z \le 102$ and mass number range $178 \le A \le 258$. The root mean square error (RMSE) values are smaller than the previous systematics. The covariance of matrix and its parameters are evaluated both in symmetric and asymmetric fission of the nuclei along with the error band.

Keywords. Kinetic energy; semi-empirical; fission.

PACS Nos 27.60.+j; 27.80.+w; 21.10.-k; 21.60.-n

1. Introduction

The fragment kinetic energy released during fission is the most fundamental and significant process which finds many nuclear applications. Many theoretical interpretations using liquid drop model [1,2] have been proposed to give experimental results. In 1959, Terrell [3] proposed the relation between average total kinetic energy $\langle E_K \rangle$ released during fission within the atomic and mass number ranges $90 \le Z \le 100$ and $229 \le A \le 254$ with the fissioning nuclei $Z^2/A^{1/3}$ term. The fission fragments were assumed to be spherical in shape with radii $r = r_0 A^{1/3}$. When the Coulomb force of repulsion overcomes nuclear force of attraction, the kinetic energy of the fragment is proportional to $Z^2/r_0 A^{1/3}$. More specifically, $\langle E_K \rangle = Z_L Z_H e^2 / r_0 (A_L^{1/3} + A_H^{1/3})$. The best fitted equation for kinetic energy proposed by Terrell [3] is as follows:

$$\langle E_K \rangle = \alpha (Z^2/A^{1/3}) + \beta \ \text{MeV}, \quad (1)$$

where $\alpha = 0.121$ and $\beta = 0$. Later, in 1963, Viola and Sikkeland [4] studied the most probable kinetic energy released during ^{12}C (125 MeV) and ^{16}O (166 MeV) induced fission reactions on different lanthanides and actinides in the atomic and mass number ranges $71 \le Z \le 102$ and $171 \le A \le 256$, respectively. In addition to $Z^2/A^{1/3}$, they also considered point charges $Z_1 e$, $Z_2 e$ whose charge centres are separated by a distance d. The least square fitting function includes the data compiled from earlier researches [1,4,5] in which $\alpha = 0.1065$ and $\beta = 20.1$. This equation is applicable for the first chance of fission and if neutron evaporation precedes fission ($x < 0.7$), then the values of α and β are 0.144 and 7.9, respectively.

Further, in 1966, Viola [6] considered that the kinetic energy released during fission depends on the shape of the fission fragments. The electrostatic interaction between the two fission fragments is given by $E_K = Z_1 Z_2 e^2 \cdot F(r)$. Here, the function $F(r)$ depends on nuclear charge distribution and shape of the fission fragments at scission points. Further, the average total kinetic energy equation was extended in the atomic and mass number ranges $67 \le Z \le 102$ and $157 \le A \le 256$, respectively [6]. The α and β values for this improved equation are 0.1071 and 22.2, respectively. The correlated E_K values were compared with the available liquid drop calculations. Later on, based on the experimental data available, Walker and Viola

[7] together proposed an expression for kinetic energy of fission fragments using least square fit and the corresponding α and β values are 0.1166 and 9.0, respectively.

By considering the kinematic coincidence technique, Viola *et al* [8] proposed an improved expression for kinetic energy of fission fragments with $\alpha = 0.1189 \pm 0.011$ and $\beta = 7.3 \pm 1.5$ in the atomic and mass number ranges $23 \leq Z \leq 120$ and $46 \leq A \leq 302$, respectively. Furthermore, Zhao *et al* [9] considered mass-symmetric expression in the atomic number range $23 \leq Z \leq 120$ and mass number range $46 \leq A \leq 302$ which is as follows:

$$\mathrm{TKE}_{\mathrm{sym}}^{\mathrm{ZHAO}} = 0.1173 \times (Z_f^2/A_f^{1/3}) + 7.5\ \mathrm{MeV} \tag{2}$$

and asymmetric expression in the atomic number range $88 \leq Z \leq 102$ and mass number range $226 \leq A \leq 260$ is as follows:

$$\mathrm{TKE}_{\mathrm{asym}}^{\mathrm{ZHAO}} = 0.1217 \times (Z_f^2/A_f^{1/3}) + 3.5\ \mathrm{MeV}, \tag{3}$$

where Z_f and A_f are the charge and mass of the fissioning nuclei, respectively. In 1991, Tavares and Terranova [10] improved total kinetic energy released during fission and fissioning nuclei whose atomic and mass number range between $22 \leq Z \leq 118$ and $42 \leq A \leq 302$, respectively is as follows:

$$\langle E_K \rangle^{\mathrm{TAV}} = \frac{Z^2}{aA^{1/3} + bA^{-1/3} + cA^{-1}}, \tag{4}$$

where the fitting parameters a, b and c are 9.39 MeV^{-1}, -58.6 MeV^{-1} and 226 MeV^{-1}, respectively.

Itkis *et al* [11] used symmetric and asymmetric fission fragments in the fusion reaction of ^{48}Ca+^{238}U. Sanders *et al* [12] investigated the most probable TKE released during fission as a function $Z^2/A^{1/3}$. Liberati *et al* [13] investigated β-decay of ^{178}Tl and also mass distribution of ^{178}Hg using Viola systematics. Usang *et al* [14,15] and Chiba *et al* [16] investigated the total kinetic energy of fission fragment mass distributions using the Langevin approach. Shimada *et al* [17] showed that the average total kinetic energy of the fission fragments decreases with increase in excitation energy. However, many empirical relations for Q-values [18], fusion barriers [19], pair production cross-section [20], $\beta^{\pm}$-decay [21,22], fusion–fission cross-sections [23] are available in the literature. From the detailed literature survey, it has been observed that there is progressive efforts from earlier researchers (Terrell [3] to Tavares [10]) to propose the best least square fit for total kinetic energy. Therefore, it is worthwhile to improve Viola systematics for the experimental data available till date. The aim of the present paper is to search for a suitable empirical formula for average total kinetic energy in the atomic number range $23 \leq Z \leq 120$ and mass number range $46 \leq A \leq 302$.

2. Analysis of experimental average total kinetic energy

The experimental data [4,8,11–16,24–27] extracted in the present work includes low-energy symmetric fission, heavy ion-induced symmetric fission at high energy, neutron-induced fission and spontaneous fission. The average total kinetic energy released during these fission reactions as a function of atomic and mass number is as follows:

$$\langle E_K \rangle \propto f(Z, A). \tag{5}$$

The function $f(Z, A)$ is evaluated by studying the variation of $\langle E_K \rangle$ as a function of $f(Z, A)$. To derive suitable empirical formula for average total kinetic energy, it is assumed that $\langle E_K \rangle$ is directly proportional to Z^m and inversely proportional to A^n as follows:

$$\langle E_K \rangle = f(Z^m/A^n). \tag{6}$$

Figure 1 represents the variation of average total kinetic energy with Z^2/A^n. The average total kinetic energy increases with increase in the ratio of Z^2/A^n. Since there is a systematic variation of average total kinetic energy with Z^2/A^n, an attempt was made to fit empirical formulae for E_K in the atomic number range $23 \leq Z \leq 120$ and mass number range $46 \leq A \leq 302$. Different values of n have been taken to identify suitable power of A. Figures 1a–1l show that the value of n varies between 0.1 and 1. The best suitable equation is selected in such a way that R^2 has the maximum value. The coefficient of determination is expressed as $R^2 = 1 - \frac{\sum(y-\hat{y})^2}{\sum(y-\bar{y})^2}$. Here y, $\hat{y}$ and $\bar{y}$ are the actual value, predicted value from the formulae and mean value of experiments. As the value of n varies between 0.1 and 1, the distribution of average total kinetic energy becomes more narrower at $n = 1/3$ with $R^2 = 0.9812$ and again inexact distributions were observed for $n \geq 0.4$. Hence, the variation of average total kinetic energy as function of Z^2/A^n is more systematic when $n = 1/3$.

Similarly, the power of Z is also identified by plotting the coefficient of determination (R^2), i.e measure of goodness of the proposed empirical formulae vs. $Z^m/A^{1/3}$. The maximum value of R^2 has been observed when $n = 1/3$ which is shown in figure 1e. Furthermore, figure 2 shows the plot of the variation of R^2 for different values of m. The systematics of R^2 for different values of m shows maximum value when $m = 2$. Hence, the systematic variation of average total kinetic energy with the function Z^m/A^n is observed when $n = 1/3$ and

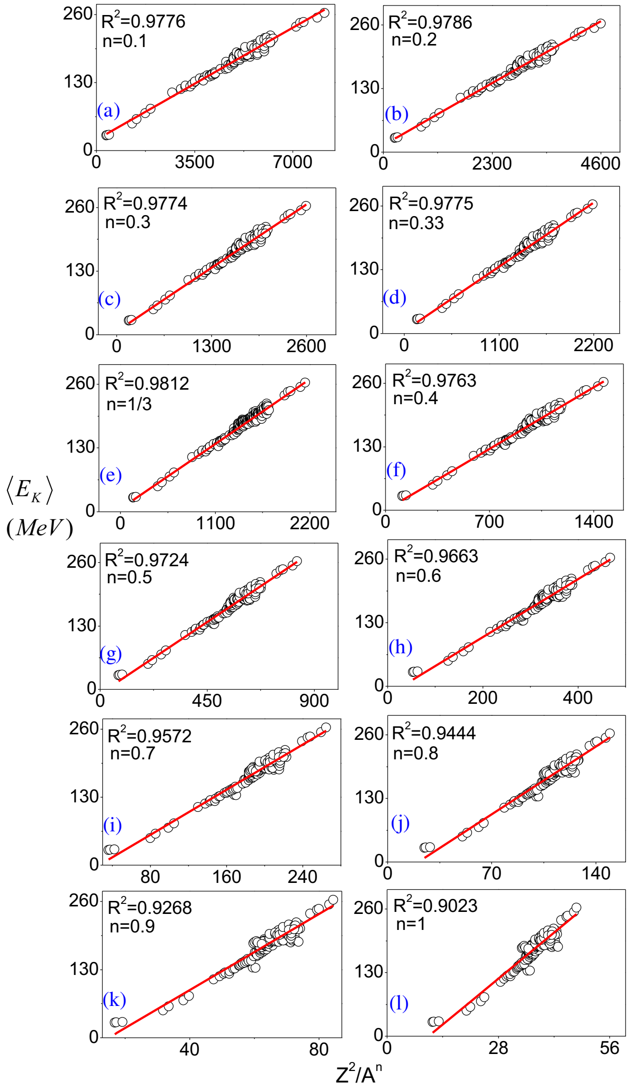

Figure 1. Variation of average total kinetic energy $\langle E_K \rangle$ of the symmetric fission is plotted as a function of Z^2/A^n. The hollow sphere represents the experimental data [11,13,24,26,28–41] and red coloured continuous line represents the value obtained from the formulae as a function of Z^2/A^n in which the value of n varies between 0.1 and 1.

$m = 2$. Hence, the best suitable function for symmetric fission is as follows:

$$\langle E_k \rangle = 0.12014 \left(\frac{Z^2}{A^{1/3}} \right) + 5.99 \text{ MeV} \quad (7)$$

and the best suitable equation for asymmetric fission in the atomic and mass number ranges $78 \le Z \le 102$ and $178 \le A \le 258$, respectively is as follows:

$$\langle E_k \rangle = 0.1367 \left(\frac{Z^2}{A^{1/3}} \right) - 18.94 \text{ MeV}. \quad (8)$$

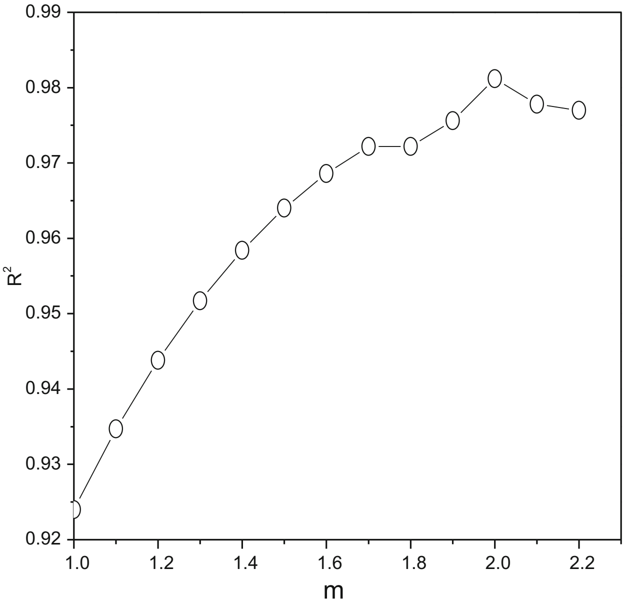

Figure 2. Variation of coefficient of determination (R^2) with different values of m in the function $Z^m/A^{1/3}$.

3. Results and discussions

We achieved the empirical formulae for average total kinetic energy for both symmetric and asymmetric fissions for experimental values available in [11,13,24,26,28–41]. The proposed formulae produce the average total kinetic energy in the atomic number range $23 \le Z \le 120$ and mass number range $46 \le A \le 302$ for symmetric and asymmetric fission reactions in the atomic number range $78 \le Z \le 102$ and mass number range $178 \le A \le 258$. Then, we have compared the improved Viola systematics (present formula) with that of the previously proposed formulae such as TERR1959 [3], VIOLA1963 [4], VIOLA1965 [6], VIOLA1985 [8], ZHAO [9] (both sym and asym) and TAV1992 [10] and it is shown in figures 3a–3g. The hollow circles in figure 3 specify the data corresponding to experimental values. The continuous line with blue colour is the estimated value obtained using TERR1959 [3]. The red coloured continuous line represents the value which is obtained from the present work. However, the improved Viola systematics from the present work is in substantial agreement with the experimental data. Similarly, figures 3b–3f also show the comparison between the improved Viola systematics with that of the previously proposed models such as VIOLA1963 [4], VIOLA1965 [6], VIOLA1985 [8], ZHAO [9](sym) and TAV1992 [10]. From these figures, in particular for VIOLA1966, VIOLA1985, ZHAO and TAV with atomic number range $23 \le Z \le 120$ and mass number range $46 \le A \le 302$, it is seen that there is a

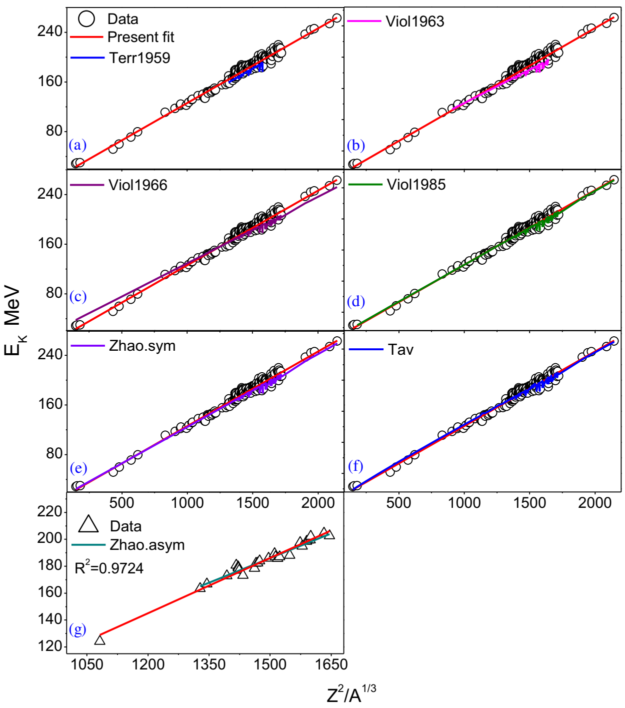

Figure 3. Comparison of $\langle E_K \rangle$ evaluated using the present fit and that with different approaches such as TERR1959 [3], VIOLA1963 [4], VIOLA1965 [6], VIOLA1985 [8], ZHAO [9] (both sym and asym), TAV1992 [10] and experimental data available in literature.

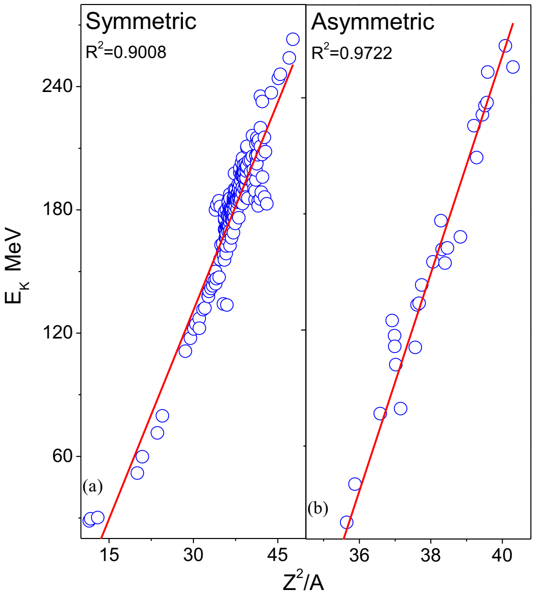

Figure 4. Variation of average total kinetic energy $\langle E_K \rangle$ plotted as a function of Z^2/A. The hollow sphere represents the experimental data [11,13,24,26,28–41] and red coloured continuous line represents the value obtained from the formulae as a function of Z^2/A.

good agreement of the present formula with the previously observed formula. Furthermore, figure 3g shows the comparison of values obtained from the empirical formula with that of the experiments and Zhao [9] for asymmetric fission process.

To verify whether the improved Viola systematics are in good agreement with that of the experiments, the statistical treatment such as root mean square error (RMSE) is evaluated as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum \log\left(\frac{T_{\mathrm{th}}}{T_{\mathrm{exp}}}\right)^{2}}, \tag{9}$$

where N is the number of fissioning nuclei. The quantified deviations for different systematics using the above statistical treatment is recorded in table 1. The range of atomic numbers, mass numbers and number of fissioning nuclei was considered during the evaluation of RMSE and is also tabulated. TERR1959 equation has been proposed in the atomic number range $90 \leq Z \leq 100$ and mass number range $229 \leq A \leq 254$ using 13 nuclei which produces RMSE of 0.17. Similarly, the limitation of VIOLA1963 formula within the atomic number range $71 \leq Z \leq 102$ and mass number range $171 \leq A \leq 256$ with 19 nuclei results in the RMSE of 0.40, whereas the VIOLA1966, VIOLA1981, VIOLA1985, ZHAO-sym and TAV gives RMSE value between 0.17 and 0.14. However, in the case of ZHAO-asym the atomic number ranges between $88 \leq Z \leq 102$ and mass number ranges between $226 \leq A \leq 260$ which brings about 0.11 deviations of RMSE. From the statistical treatment it is observed that the improved Viola systematics within the atomic and mass number ranges $78 \leq Z \leq 102$ and $178 \leq A \leq 258$ have less value corresponding to RMSE where coefficient of determinant (R^2) values for both symmetric and asymmetric fission were found to be 0.98115 and 0.97239, respectively. Hence, the average total kinetic energy during fission is more accurately estimated with the simple input of A and Z values in the proposed empirical formulae.

The fissility parameter is the key factor which decides fission barrier height and whether the nucleus is unstable towards fission or not. Hence, the role of the fissility parameter (Z^2/A) on the average total kinetic energy released is studied and exhibited in figure 4. We have fitted linear equation for symmetric and asymmetric fission with R^2 value of 0.9008 and 0.9127, respectively. Hence, from figures 1, 3 and 4 it is noticed that the value of R^2 is maximum when the chosen function is $Z^2/A^{1/3}$ rather than Z^2/A. Hence, in all further investigations, we considered $Z^2/A^{1/3}$ both for symmetric and asymmetric fission.

Table 1. Deviation of RMSE obtained using different systematics such as TERR1959 [3], VIOLA1963 [4], VIOLA1965 [6], VIOLA1985 [8], ZHAO [9] (both sym and asym), TAV1992 [10] and the present work (PW) with that of the available experiments in the atomic number range $23 \leq Z \leq 120$ and mass number range $46 \leq A \leq 302$.

Model	Z	A	N	RMSE
TERR1959	90–100	229–254	13	0.17
VIOL1963	71–102	171–256	19	0.4
VIOL1965	67–102	157–256	41	0.17
VIOL1985	26–120	46–302	66	0.14
ZHAO-sym.	23–120	46–302	93	0.15
ZAHO-asym.	88–102	226–258	26	0.11
TAV	22–118	42–302	99	0.14
PW-sym.	23–120	46–302	244	0.13
PW-asym.	78–102	178–258	30	0.09

The predictability of the constructed formula is also assessed by calculating the covariance matrix and its parameters. The evaluated covariance matrix for the symmetric case is given as

$$(\mathrm{cov})_{\mathrm{sym}} = \begin{bmatrix} 973.31 & 945.13 \\ 945.13 & 939.31 \end{bmatrix}.$$

The eigenvalues of this matrix gives covariance matrix of the parameters and these are $\lambda_1 = 1901.1$ and $\lambda_2 = 11.02$. For the asymmetric case, the evaluated covariance matrix is

$$(\mathrm{cov})_{\mathrm{asym}} = \begin{bmatrix} 120.84 & 115.92 \\ 115.92 & 115.92 \end{bmatrix}.$$

The evaluated covariance matrix of the parameters are $\lambda_1 = 234.02$ and $\lambda_2 = 2.75$. The close reproduction of experimental values using the present empirical formulae would be done by the analysis of percentage of deviation as follows:

$$\langle \Delta E_K \rangle = \frac{\langle E_K \rangle_{\mathrm{Formula}} - \langle E_K \rangle_{\mathrm{Exp}}}{\langle E_K \rangle_{\mathrm{Exp}}}, \tag{10}$$

where $\langle E_K \rangle_{\mathrm{Formula}}$ and $\langle E_K \rangle_{\mathrm{Exp}}$ are the average total kinetic energies obtained from the present formula and experiments, respectively. Figure 5 shows the percentage of deviation obtained from the present formulae from that of the available experiments for both (a) symmetric and (b) asymmetric fission of nuclei in the atomic number range $23 \leq Z \leq 120$ and mass number range $46 \leq A \leq 302$. The deviation observed in the case of average total kinetic energy in symmetric fission is $\pm 6\%$ and in the case of asymmetric fission the deviation is found to be $\pm 3\%$. The quality of the average TKE using different formulae is tested using Pearson's chi-squared test formula, i.e., $\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i}$. Here, O_i and E_i are the experimentally observed and fitted data for the ith-type of reaction. The term n is the total number of observations. In the case of symmetric fission, we have considered about 244 values for which χ^2 is evaluated using different formulae available in literature and the present work. The χ^2 values in the symmetric case is tabulated in table 2. By comparing different χ^2 values it is clearly seen that χ^2 is larger for VIOLA 1965 and least for the present work. Similarly, for the asymmetric case, we noticed 0.065 and 0.039 for ZHAO and the present work, respectively.

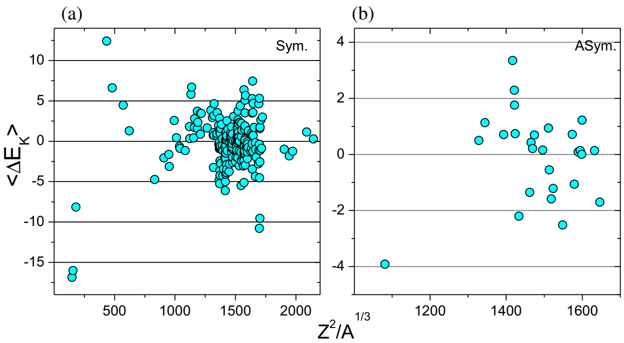

Figure 5. Percentage of deviation obtained from the present formulae with that of the available experiments for both (**a**) symmetric and (**b**) asymmetric fission of the nuclei.

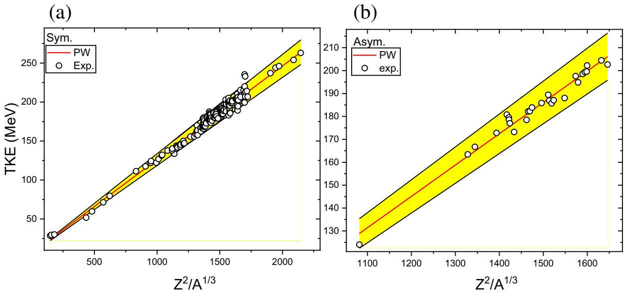

Figure 6. Comparison of the present work (PW) with that of the experiments for both (**a**) symmetric and (**b**) asymmetric fission of the nuclei along with the error band.

Furthermore, the comparison of the present formulae with that of the experiments for both (a) symmetric and (b) asymmetric fission of the nuclei along with the error band is shown in figure 6. Hence, our proposed empirical formula produces average total kinetic energy of both symmetric and asymmetric fission with less deviation than that of the other formulae such as TERR1959 [3], VIOLA1963 [4], VIOLA1966 [6], VIOLA1985 [8], ZHAO [9] (both sym and asym) and TAV1992 [10]. The constructed formula for the average total kinetic energy of both symmetric and asymmetric fission is applicable in the atomic number range $23 \leq Z \leq 120$ and mass number range $46 \leq A \leq 302$.

Table 2. Tabulation of χ^2 values obtained in symmetric fission from different formulae available in literature and the present work (PW) with that of the available experiments.

TERR1959	VIOLA1963	VIOLA1965	VIOLA1985	ZHAO	TAV	PW
0.259	0.322	0.324	0.148	0.201	0.164	0.126

4. Conclusions

A new improved formula of Viola systematics has been estimated in the atomic number range $23 \leq Z \leq 120$ and mass number range $46 \leq A \leq 302$ based on the experimental data available in literature. Extensive experimental data include low-energy symmetric fission, heavy ion-induced symmetric fission at high-energy, neutron-induced fission and spontaneous fission. The proposed formula for the average total kinetic energy for both symmetric and asymmetric fission is found to be more adequate to reproduce experimental values. From the statistical treatments, it is observed that the present formulae produce less deviation than the previously proposed formulae. The standard deviation obtained from the empirical formulae varies between ±6% and ±3% in symmetric and asymmetric fission, respectively. The covariance of the matrix and its parameters were evaluated in both symmetric and asymmetric fission of nuclei. The plot of the error band of the new formulae is also shown. Hence, from the detailed investigations, the average is more accurately estimated with the simple inputs of A and Z values in the proposed empirical relations.

References

[1] N Bohr, *Phys. Rev.* **56(5)**, 426 (1939)
[2] S Frankel and N Metropolis, *Phys. Rev.* **72(10)**, 914 (1947)
[3] J Terrell, *Phys. Rev.* **113(2)**, 527 (1959)
[4] V E Viola and T Sikkeland, *Phys. Rev.* **130(5)**, 2044 (1963)
[5] H C Britt, H E Wegner and J Gursky, *Phys. Rev. Lett.* **8(3)**, 98 (1962)
[6] V E Viola, *Nuclear Data Sheets A* **1**, 391 (1965)
[7] M L Walker and V E Viola, *Indiana Nuclear Chemistry Report* INC-40007-6 (1981)
[8] V E Viola, K Kwiatkowski and M Walker, *Phys. Rev. C* **31(4)**, 1550 (1985)
[9] Y L Zhao, H Nakahara, K Sueki, Y Nagame and I Nishinaka, *Advanced Science Research Center, Japan Atomic Energy Research Institute* (2000)
[10] O A P Tavares and M L Terranova, *Il Nuovo Cimento A (1965–1970)* **105(4)**, 723 (1992)
[11] M G Itkis, E Vardaci, I M Itkis, G N Knyazheva and E M Kozulin, *Nucl. Phys. A* **944**, 202 (2015)
[12] S J Sanders, A S De Toledo and C Beck Christian, *Phys. Rep.* **311(6)**, 487 (1999)
[13] V Liberati *et al*, *Phys. Rev. C.* **88(4)**, 044322 (2013)
[14] M D Usang, F A Ivanyuk, C Ishizuka and S Chiba, *Sci. Rep.* **9(1)**, 1 (2019)
[15] M Usang, F Ivanyuk, C Ishizuka and S Chiba, *EPJ Web Conf.* **146**, 04025 (2017)
[16] S Chiba, M D Usang, C Ishizuka, F Ivanyuk and Z Xuan, *EPJ Web Conf.* **242**, 03004 (2020)
[17] K Shimada, C Ishizuka, F A Ivanyuk and S Chiba, *Phys. Rev. C* **104(5)**, 054609 (2021)
[18] H C Manjunatha, A M Nagaraja, N Sowmya and K N Sridhar, *Indian J. Phys.* **96**, 1237 (2022)
[19] H C Manjunatha, K N Sridhar, N Nagaraja and N Sowmya, *The Eur. Phys. J. Plus* **133(6)**, 1 (2018)
[20] H C Manjunatha, L Seenappa, N Sowmya, K N Sridhar and B M Chandrika, *Mod. Phys. Lett. A* **35(34)**, 2050285 (2020)
[21] X Zhang, Z Ren, Q Zhi and Q Zheng, *J. Phys. G: Nucl. Part. Phys.* **34(12)**, 2611 (2007)
[22] S Zong-Qiang, S Liang-Ping, M Ying, H Ji-Gang and Q Jian-Fa, *Chin. Phys. C* **38(12)**, 124101 (2014)
[23] H C Manjunatha and N Sowmya, *Pramana – J. Phys.* **90(5)**, 1 (2018)
[24] S Chiba, M D Usang, C Ishizuka, F Ivanyuk and Z Xuan, *AIP Conf. Proc.* **2319(1)**, 080015 (2021)
[25] A Andreyev *et al*, *Phys. Rev. C* **87**, 014317 (2013)
[26] B B Back, *J. Phys.: Conf. Ser.* **282**, 012003 (2011)
[27] V E Viola and G T Seaborg, *J. Inorg. Nucl. Chem.* **28(3)**, 697 (1966)
[28] J R Nix and A J Sierk, *Nucl. Phys. A* **428**, 161 (1984)
[29] M R Lane *et al*, *Phys. Rev. C.* **53(6)**, 2893 (1996)
[30] S D Beizin, S V Zhdanov, M G Itkis, V N Okolovich, G N Smirenkin and M I Subbotin, *Sov. J. Nucl. Phys. (English Translation)* **53(3)**, 411 (1991)
[31] M G Itkis, V N Okolovich and A Ya, *Z. Phys. A* **320**, 433 (1985)
[32] I Nishinaka, Y Nagame, K Tsukada, H Ikezoe, K Sueki, H Nakahara, M Tanikawa and T Ohtsuki, *Phys. Rev. C* **56(2)**, 891 (1997)
[33] P M Kaldiani, *Phys. Rev. C* **102(4)**, 044612 (2020)
[34] C E Bemis *et al*, *Phys. Rev. C* **15(2)**, (1977)
[35] J P Unik, J E Gindler, L E Glendenin, K F Flynn, A Gorski and R K Sjoblom, *Physics and chemistry of fission* (1973)
[36] D C Hoffman *et al*, *Phys. Rev. C* **21(3)**, 972 (1980)
[37] J F Wild *et al*, *J. Alloys Compd* **213**, 86 (1994)

[38] J Elseviers *et al*, *Phys. Rev. C* **88(4)**, 044321 (2013)

[39] M D Usang, F Ivanyuk, C Ishizuka and S Chiba, *Energy Proc.* **131**, 299 (2017)

[40] A N Andreyev *et al*, *Phys. Rev. C* **87(1)**, 014317 (2013)

[41] J P Unik and J E Gindler, https://www.osti.gov/biblio/4010075 (1971)