6 Concluding Remarks

Due to the new experimental data have been available in last years, the evaluated data were considerably improved, especially for the cross sections of (n,2n) reaction and inelastic scattering to some discrete levels.

Acknowledgments

The author would like to thank Prof. LIU Tingjin for his much helps with this work, also thank Prof. Shen Qingbiao for his help in the DWUCK code calculation.

References

[1] ZHANG Jingshang. Nucl. Sci. Eng., 1993, 114; 55~63

[2] Nuclear Data Sheets, 43, 383, 1984; 61, 93, 1990; 47,797,1986; 63,723,1991; 50,719,1987

[3] R.Koehler et al. Phys. Rev., C35,1646(1987)

[4] D.J.Horen et al. Phys. Rev., C18,722(1978)

[5] B.A.Benetskij et al. 77Kiev 2,47(1977)

[6] Ju.V.Dukarevich et al. Nucl. Phys., A92(2),433(1967)

[7] R.B.Day et al. EXFOR 12191.1010(1965)

[8] D.J.Horen et al. Phys. Rev., C29,2126(1984)

[9] P.T.Guenther et al. Nucl. Sci. Eng., 65,174(1978)

[10] Y.Tomita et al. EXFOR 20304.002(1973)

[11] R.B.Day et al. EXFOR 12191.009(1965)

[12] E.Almen-Ra. et al. Atomnaya Energiya, 503(1975)

[13] L.Cranberg et al. Phys. Rev.,159,969(1967)

[14] W.E.Kinney et al. ORNL-4909(1974)

[15] J.Frehaut et al. BNL-NCS-51245(1980)

[16] A.A.Filatenkov et al. EXFOR 41240.069(1997)

[17] LU Hanlin et al. C. Nucl. Phys., 12,269(1990)

[18] Y.Ikeda et al. JAERI-1312(1988)

[19] K.Kobayashi et al. 88MITO,261(1988)

[20] T.B.Ryves et al. ANE 17,107(1990)

[21] P.Decowaki et al. Nucl. Phys., A204,121(1973)

[22] G.N.Maslov et al. EXFOR 40136.001(1972)

[23] A.A.Drushinin et al. EXFOR 40171(1971)

[24] W.Dilg at al. Nucl. Phys., A118,9(1968)

[25] F.J.Vaughn et al. EXFOR 12223.002(1963)

[26] S.M.Qaim EY AL. Nucl. Phys., A257(2),233(1976)

[27] T.W.Woo et al. 79KNOX, 853(1979)

[28] SHEN Qingbiao et al. CNDP, No.7, 43(1993)

[29] ZHUANG Youxiang et al. Chinese Physics, 8, 721-727(1988)

Evaluation of Nuclear Fission Barrier Parameters for 17 Nuclei

WANG Shunuan
China Nuclear Data Center, CIAE, P.O.Box 275(41) Beijing, 102413
e-mail wsn@iris.ciae.ac.cn

As we know well that modern nuclear installations and applications have reached a high degree of sophistication. The effective safe and economical design of these technologies require detailed and reliable design calculations. The accuracy of these calculations is largely determined by the accuracy of the basic nuclear and atomic input parameters. In order to meet the needs on high energy fission cross section, fission spectra in waste disposal, transmutation, radioactive beams physics and so on, 17 nuclei fission barrier parameters were collected from the literature based on different experiments and measurements as well as some theory models, and evaluated. The 17 nuclei include some ultra neutron-deficient nuclei and some short half-life radioactive ones. These parameters can be used for nuclear model calculation of nuclear reaction cross sections, spectra and other related important physical quantities required by a large variety of applications.

In fission barrier parameters research for the ultra neutron-deficient nuclei[1], the reduced probabilities of the delayed fission channel $P_{\beta\mathrm{df}}$ for ${}^{188}_{83}\mathrm{Bi}$ and ${}^{196}_{85}\mathrm{At}$ were determined from experimental data as 3.4×10^{-4} and 8.4×10^{-4}, respectively. The comparison of the obtained and calculated values of $P_{\beta\mathrm{df}}$ allows one to estimate the fission barrier parameters for ${}^{188}\mathrm{Pb}^{82}$ and ${}^{196}\mathrm{Po}^{84}$ by using statistical model calculations. The results are as the following:

$$
\begin{aligned}
&{}^{188}_{82}\mathrm{Pb} \quad B_\mathrm{f} = 9.6 \pm 0.9\,\mathrm{MeV} \\
&{}^{196}_{84}\mathrm{Po} \quad B_\mathrm{f} = 8.6 \pm 0.9\,\mathrm{MeV} \quad \text{(case (1))} \\
&\qquad\quad\ B_\mathrm{f} = 8.2 \pm 0.6\,\mathrm{MeV} \\
&\qquad\quad\ B_\mathrm{f} = 7.4 \pm 0.6\,\mathrm{MeV} \quad \text{(case(2))} \\
&\qquad\qquad \text{with} \quad \hbar\omega = 1\,\mathrm{MeV}
\end{aligned}
$$

Here, case (1) and case (2) are for two different assumptions about $\Gamma_\mathrm{f}/\Gamma_\mathrm{tot}$ in statistical model calculations. Γ_f is the fission width and Γ_tot is total decay width. In case (1), $\Gamma_\mathrm{f} = 0.5\Gamma_\mathrm{tot}$ was used. In case (2), Γ_f was calculated by using an expression recommended in Ref. [2] in which the Hill-Wheeler formula was used and the radioactive capture decay width Γ_γ was calculated by using the formula presented by A.Stoliry et al.[3] . In the whole statistical model calculations, the Gilbert-Cameron level density formula was utilized.

The liquid-drop fission barrier B_f^LD is smaller than the full fission barrier by a value of the shell correction, which is equal to 1.2 MeV for ${}^{188}_{82}\mathrm{Pb}$ and 1.8 MeV for ${}^{196}_{84}\mathrm{Po}$ according to the calculations of Ref.[4]. The results of B_f^LD obtained from the experimental data on the delayed fission probability in Ref.[1] in case (2) and the corresponding shell correction calculation mentioned above, are in good agreement with fission barrier obtained from data on cross section of heavy ion reactions for these nuclei[5,6]. The values of B_f^LD obtained from the experimental data on the delayed fission data are also not in contradiction with the assumption about a more rapid decrease of the fission barrier for neutron-deficient nuclei than it is predicted by the theory. Besides, there should be some other factors that can influence the fission barrier height. These factors could be, for instance, the resonance structure of the β-decay strength function; the influence of spin states and the structure of energy levels as well as occupied at β-decays on the value of Γ_f; the contribution of delayed charged particle like proton and alpha decays to the value of Γ_tot. But all of these factors can cause only an additional decrease of the barriers. Therefore, based on the above analysis we recommend fission barrier parameters of Ref. [1] in case 2 for ${}^{188}_{82}\mathrm{Pb}$ and ${}^{196}_{84}\mathrm{Po}$ as the following:

$$
\begin{aligned}
&{}^{188}_{82}\mathrm{Pb} \quad B_f = 8.2 \pm 0.6\,\mathrm{MeV} \\
&{}^{196}_{84}\mathrm{Po} \quad B_f = 7.4 \pm 0.6\,\mathrm{MeV} \ \text{(with } \hbar\omega = 1\,\mathrm{MeV}\text{)}
\end{aligned}
$$

M. Thoennessen and G. F. Bertsch presented the empirical domain of validity of statistical theory[7] , as applied to fission data on pre-fission neutron, charged particle and γ-ray multiplicity. Systematic analysis are found of the threshold excitation energy for the appearance of non-statistical fission. In this paper, they search for systematic trends of the validity of the statistical model by assembling data over a wide range of masses and fissilities. In particular, they tabulated the threshold excitation energy E_thresh marking the upper limit of the energies where the statistical theory applies; they extracted and analyzed the threshold excitation energy and the fission barrier from a variety of different measurements. They listed the analyzed fission system following fusion evaporation reactions. The pre-fission neutron, charged particle and GDR γ-ray multiplicity measurements are also included (See Table 1).

Table 1 Different Reactions, Compounds and their Paramenters

Reaction	CN	x_fiss	E_thresh	B_f	Ref.
${}^{16}\mathrm{O}+{}^{142}\mathrm{Nd}$	${}^{158}\mathrm{Er}$	0.60	80±10	11.2±2.0	[8]
${}^{18}\mathrm{O}+{}^{150}\mathrm{Sm}$	${}^{168}\mathrm{Yb}$	0.60	85±5	10.4±2.4	[9]
${}^{19}\mathrm{F}+{}^{159}\mathrm{Tb}$	${}^{178}\mathrm{W}$	0.64	80±10	10.3±2.3	[10]
${}^{19}\mathrm{F}+{}^{169}\mathrm{Tm}$	${}^{188}\mathrm{Pt}$	0.67	80±5	7.1±1.2	[10]
${}^{28}\mathrm{Si}+{}^{170}\mathrm{Er}$	${}^{198}\mathrm{Pb}$	0.70	60±5	7.1±1.1	[9]
${}^{19}\mathrm{F}+{}^{181}\mathrm{Ta}$	${}^{200}\mathrm{Pb}$	0.70	65±5	8.6±1.0	[9]
${}^{30}\mathrm{Si}+{}^{170}\mathrm{Er}$	${}^{200}\mathrm{Pb}$	0.70	55±5	7.0±0.9	[9]
${}^{18}\mathrm{O}+{}^{192}\mathrm{Os}$	${}^{210}\mathrm{Po}$	0.71	60±5	8.0±0.8	[9]
${}^{16}\mathrm{O}+{}^{197}\mathrm{Au}$	${}^{213}\mathrm{Fr}$	0.74	45±5	6.2±0.6	[11]
${}^{16}\mathrm{O}+{}^{208}\mathrm{Pb}$	${}^{224}\mathrm{Th}$	0.76	30±5	5.5±0.5	[12]
${}^{19}\mathrm{F}+{}^{232}\mathrm{Th}$	${}^{251}\mathrm{Es}$	0.83	20±10	1.8±0.2	[10]
$\mathrm{p}+{}^{238}\mathrm{U}$	${}^{239}\mathrm{Np}$	0.78	20±2	4.3±0.1	[13]
${}^{28}\mathrm{Si}+{}^{164}\mathrm{Er}$	${}^{192}\mathrm{Pb}$	0.72	58±5	5.9±0.9	[14]
${}^{28}\mathrm{Si}+{}^{164}\mathrm{Er}$	${}^{192}\mathrm{Pb}$	0.72	53±5	6.7±0.9	[14]
${}^{19}\mathrm{F}+{}^{181}\mathrm{Ta}$	${}^{200}\mathrm{Pb}$	0.70	68~84	8.4~6.5	[15]
${}^{32}\mathrm{S}+{}^{184}\mathrm{W}$	${}^{216}\mathrm{Th}$	0.78	72~85	2.6~1.7	[16]
${}^{16}\mathrm{O}+{}^{208}\mathrm{Pb}$	${}^{224}\mathrm{Th}$	0.76	30~40	5.5~4.5	[17]
${}^{32}\mathrm{S}+{}^{208}\mathrm{Pb}$	${}^{240}\mathrm{Cf}$	0.84	67~80	0.7~0.4	[18]

CN: Compound Nuclei ; x_fiss :Fissilities; E_thresh:Threshold energies; B_f:Mean fission barrier; All energies are in MeV, the same below.

In present paper we are interested in compound nuclei (CN), fissilities($x_{\rm fiss}$), and mean fission barrier $B_{\rm f}$ listed in Table 1. We notice that there are two values taking from different measurements for ^{200}Pb and ^{192}Pb, respectively. In this case we recommend the mean value of them with weight and its external error. Thus we have $B_{\rm f}$ =7.8±0.67 MeV for ^{200}Pb and 6.3±0.64 MeV for ^{192}Pb. The result of $B_{\rm f}$=7.8±0.67 MeV for ^{200}Pb is just in the range of 8.4~6.5 MeV taking from measurement[15] (also listed in Table 1). It is clear that the results from different works are in agreement with each other. From the listed results in table 1, it can be seen clearly also that the result of $B_{\rm f}$ =5.5±0.5 MeV for ^{224}Th taking from Ref. [12] is in agreement with the result of $B_{\rm f}$=5.5~4.5MeV taking from Ref. [17].

Table 2 listed the results of peripheral reactions ^{40}Ar+^{232}Th taking from Ref. [19].

Table 2 ^{40}Ar+^{232}Th Reactions and their Different Compounds and Paramenters

Reaction	CN	$x_{\rm fiss}$	$E_{\rm thresh}$	$B_{\rm f}$	Ref.
^{40}Ar+^{232}Th	^{225}Fr	0.73	47±4	6.0±0.6	[19]
^{40}Ar+^{232}Th	^{228}Ra	0.74	34±2	5.3±0.5	[19]
^{40}Ar+^{232}Th	^{228}Ra	0.74	46±6	5.9±0.3	[19]
^{40}Ar+^{232}Th	^{228}Ra	0.74	66±7	7.0±0.2	[19]
^{40}Ar+^{232}Th	^{230}Ac	0.75	18±2	4.7±0.4	[19]
^{40}Ar+^{232}Th	^{230}Ac	0.75	21±3	5.2±0.3	[19]
^{40}Ar+^{232}Th	^{230}Ac	0.75	32±4	6.2±0.2	[19]

There are three values of mean fission barrier $B_{\rm f}$ for ^{228}Ra and ^{230}Ac, respectively. We took their mean value with weight and their external errors as the following: 6.07±0.16 MeV for ^{228}Ra and 5.37±0.15 MeV for ^{230}Ac, respectively.

In general, the parameters $B_{\rm f}$ listed in Table 1 and 2 are with $\hbar\omega = 0.5 \sim 1.0\,\mathrm{MeV}$.

According to the analysis and review above, we recommended fission barrier parameters for 17 nuclei, including some ultra neutron-deficient nuclei and some short half-life radioactive ones, which could be used in nuclear data calculations and evaluations in applications on needs. The recommended parameters are listed in Table 3.

Table3 Recommended fission barrier Paramenters

CN	$x_{\rm fiss}$	$B_{\rm f}$ (MeV)	$\hbar\omega$ (MeV)	Ref.
^{158}Er	0.60	11.2±2.0	0.5~1.0	[7,8]
^{168}Yb	0.60	10.4±2.4	0.5~1.0	[7,9]
^{178}W	0.64	10.3±2.3	0.5~1.0	[7,10]
^{188}Pt	0.67	7.1±1.2	0.5~1.0	[7,10]
^{188}Pb	0.72	8.2±0.6	1.0	[1~6]
^{192}Pb	0.72	6.3±0.64	0.5~1.0	[7,14]
^{196}Po	0.73	7.4±0.6	0.5~1.0	[1~6]
^{198}Pb	0.70	7.1±1.1	0.5~1.0	[7,9]
^{200}Pb	0.70	7.8±0.67	0.5~1.0	[7,9,15]
^{210}Po	0.71	8.0±0.8	0.5~1.0	[7,9]
^{213}Fr	0.74	6.2±0.6	0.5~1.0	[7,11]
^{224}Th	0.76	5.5±0.5	0.5~1.0	[7,12,17]
^{225}Fr	0.73	6.0±0.6	0.5~1.0	[19]
^{228}Ra	0.74	6.07±0.16	0.5~1.0	[19]
^{230}Ac	0.75	5.37±0.15	0.5~1.0	[19]
^{239}Np	0.78	4.3±0.1	0.5~1.0	[13]
^{251}Es	0.83	1.8±0.2	0.5~1.0	[10]

References

[1] A.N. Andreyev, D.D. Bogdanov, S. Saro, et al., Phys. Letter B 312,49-52(1993)

[2] L.G. Moretto, Proc. Symp. On Phys. And Chemi. of Fission (Rochester NY.)1973; IAEA report IAEA SM-174/204(IAEA, Vienna) p.329

[3] A.Stolory and J.A. Harvey, Phys. Rev.108, 353(1957)

[4] P. Moller and J. R. Nix, Los Alamos Preprint LA-YR-86- 3983(1986)

[5] A.N. Andreyev et al., JINR Rapid Commun. 2(53), 35(1992)

[6] A.N. Andreyev et al., Yad Fiz. 52,640(1990)

[7] M.Thoennessen and G. F. Bertsch, Phys. Rev. Letter, Vol.71, No.26, 4303(1993)

[8] A. Ganron et al., Phys. Rev. C35, 579(1987)

[9] D.J. Hinde, R. J. Xharity, G. S. Foote et al., Nucl. Phys. A452, 550(1986)

[10] J. O. Newton, D. J. Hinde, R. J. Charity et al., Nucl. Phys. A483, 126(1988)

[11] D. J. Hinde, D. Hilscher and Rossner, Nucl. Phys. A502, 497c(1989)

[12] D. Hilscher and Rossner, Ann. Phys. Fr17, 471(1992)

[13] M. Strecker, R. Wien, P. Plischke et al., Phys. Rev. C41, 2172(1990)

[14] J. P. Lestone, J.R. Leigh, J. O. Newton et al., Phys. Rev. Letter, 67, 1078(1991)

[15] R. Butsch, M. Thoennessen, D. R. Chakrabarty et al., Phys. Rev. C41, 1530(1990)

[16] I. Dioszegi, D. J. Hofman, C.P. Montoya et al., Phys. Rev. C46, 627(1992)

[17] M. Thoennessen, D. R. Chakrabarty, M.G. Herman et al., Phys. Rev. Letter, 59, 2860(1987)

[18] D.J. Hofman, B.B. Back, I. Dioszegi, et al., (to be published)

[19] E. -M. Eckert et al., Phys. Rev. Letter, 64, 2483(1990)