Estimates of fission barrier heights for neutron-deficient Po to Ra nuclei produced in fusion reactions

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Abstract. The cross section data for fission and evaporation residue production in fusion reactions leading to nuclei from Po to Ra have been considered in a systematic way in the framework of the conventional barrier-passing (fusion) model coupled with the statistical model. The cross section data obtained in very asymmetric projectile-target combinations can be described within these models rather well with the adjusted model parameters. In particular, one can scale and fix the macroscopic (liquid-drop) fission barrier heights (FBHs) for nuclei involved in the de-excitation of compound nuclei produced in the reactions. The macroscopic FBHs for nuclei from Po to Ra have been derived in the framework of such analysis and compared with the predictions of various theoretical models.

1. Introduction

The comparison of fission barrier heights (FBHs) calculated in a region between two neutron shells (126 ≤ N ≤ 184) reveals a large spread in their predictions for exotic neutron-rich nuclei [1]. At the same time, a reasonable description of FBHs close to the stability line (where model parameters are tuned to experimental data) is usually accomplished [2]. Large discrepancies between predictions of different models and FBHs derived for neutron-deficient nuclei produced in nuclear reactions were also observed earlier [3]. The differences between different calculations for extremely neutron-rich (hypothetical) Po nuclei reach 30 MeV. Such uncertainty results in completely different scenarios as far as the r-process termination by fission is considered [4]. So the study of the isotopic dependence of FBHs for nuclei far from the stability is one of the most important tasks in modern fission studies. Unfortunately, such studies are very difficult for neutron-rich nuclei due to their very low production rates [5,6]. At the same time, the isotopic dependence of FBHs can be studied in the more readily accessible region of neutron-deficient nuclei produced in heavy ion (HI) fusion reactions.

2. Statistical model considerations

Within statistical model (SM) considerations production cross sections for the neutron-deficient heavy nuclei formed in very asymmetric projectile-target fusion reactions are mainly determined by level density parameters and FBHs for nuclei involved in compound nucleus (CN) de-excitation chains. An analysis of the cross section data for evaporation residues (ERs) and fission with the use of the SM approximations [7] implies the FBH scaling of the liquid-drop (LD) barriers: \( B_{f}(L) = k_{f}B_{LD}(L) - \Delta W_{gs} \), where \( k_{f} \) is a scaling factor at the rotating LD barriers \( B_{LD}(L) \) [8] and \( \Delta W_{gs} \) is the ground state shell correction. The macroscopic components of the barriers \( B_{m} = k_{m}B_{LD} \) derived from the analysis of Fr and Ra data [9,10] are lower than any predictions [2,3,11] (apart the values from [12]). The \( B_{m} \) values are about a smooth function of \( N \), e.g., for Fr nuclei \( k_{l} \) is reduced from 0.85 to 0.8, in going from \( N = 131 \) to 117 (Fig. 1).

The data shown in Fig. 1 do not reveal any manifestation of the effect of the collective enhancement in the nuclear level density (CENLD). This effect is expected to be pronounced in the vicinity of the \( N = 126 \) spherical shell as a decrease in the ER production cross sections, as it follows, e.g., from [5]. Such decrease is not observed in the ER cross section data obtained in the fusion experiments [9,10] and, respectively, it is not expressed as a possible relative reduction in the \( B_{m} \) values (SM [7] does not take into account the CENLD effect in the calculated cross sections).

The similar analysis of the ER and fission data for Po nuclei in a wide region of \( N (105 \leq N \leq 26) \) [14] shows a sizable reduction in the \( B_{m} \) values for neutron-deficient nuclei as compared to any predictions. This analysis includes ER data obtained in nearly symmetric and massive asymmetric projectile-target combinations leading to the most neutron-deficient nuclei. The possibility of quasi-fission (QF) effects [15] leading to the fusion probability \( P_{ fus } < 1 \) is not excluded in these reactions. Thus the comparison of the ER production cross sections obtained in the \( ^{16}\text{O} + ^{180}\text{W} \) and \( ^{48}\text{Ca} + ^{154}\text{Sm} \) reactions leading to the \( ^{202}\text{Pb} \) CN [16,17] shows directly that \( P_{ fus } < 1 \) for the latter. These \( P_{ fus } \) values differ noticeably from those derived with the fission study [18] and obtained in the theoretical calculations [19] (Fig. 2).

3. \(^{3,4}\text{He} + \text{Pb,Bi} \) data analysis

The \(^{3,4}\text{He} + \text{Pb,Bi} \) reactions leading to Po, At compound nuclei can be the most suitable for the \( B_{m} \) estimates in the light of the above mentioned QF effects observed in HI fusion reactions (QF may reduce the observable ER
Figure 1. Bottom panels: the macroscopic fission barriers $B_m$ for Fr and Ra nuclei derived with the SM [7] analysis of ER and fission cross section data obtained in the HI fusion reactions [9,10] in comparison with the predictions [2,3,11,12]. Upper panels: the ground-state shell corrections $\Delta W_{gs}$ in the vicinity of spherical nuclei corresponding to $|\beta_2| < 0.15$ [13].

Figure 2. The fusion probabilities $P_{fus}$ extracted from the fission data obtained in the $^{48}$Ca+$^{154}$Sm reaction [18] and similar values derived with the comparison of the ER cross sections measured in the same reaction and those obtained in $^{16}$O+$^{186}$W [16,17] (symbols). $P_{fus}$ calculated in the framework of the DNS concept [19] is also shown for comparison by solid line.

Figure 3. The production cross sections for $^{211-208}$Po isotopes as measured by different authors in the $^{208}$Pb$(^3,^4$He,$xn$) reactions [21] (symbols). The evaporative excitation functions calculated with the SM [7] using the best choice of the nuclear potential parameters and different sets of the CN-decay parameters as obtained in the present work (lines).
Table 1. The parameter values of the nuclear exponential potential \( V_0 \) (MeV/fm), \( r_0 \) (fm), \( \sigma \left( r_0 \right) / \left\langle r_0 \right\rangle \) and \( L_{cr} \) (MeV/fm) providing the best fit of the excitation functions calculated with SM to the \( ^{3.4}\text{He} + \text{Pb,Bi} \) data [20,21].

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Target</th>
<th>( V_0 ) (MeV/fm)</th>
<th>( r_0 ) (fm)</th>
<th>( \sigma \left( r_0 \right) / \left\langle r_0 \right\rangle )</th>
<th>( L_{cr} ) (MeV/fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{4}\text{He} + ^{208}\text{Pb} )</td>
<td>( ^{208}\text{Bi} )</td>
<td>80</td>
<td>1.12</td>
<td>2.3</td>
<td>3.3</td>
</tr>
<tr>
<td>( ^{4}\text{He} + ^{209}\text{Bi} )</td>
<td>( ^{209}\text{Bi} )</td>
<td>60</td>
<td>1.25</td>
<td>8.5</td>
<td>16</td>
</tr>
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</table>

value determining the cross sections calculated for fission and for the \( 6n \sim 10n \) evaporative channels.

In Table 1 the main parameter values of the nuclear exponential potential [22] and the values of the critical angular momentum \( L_{cr} \) providing the best fit of the excitation functions calculated with SM [7] to the data obtained in the \( ^{3.4}\text{He} + \text{Pb,Bi} \) reactions [20,21] are shown. These values, along with the data in Table 1, provide the best fit of the calculated excitation functions to the data [20,21].

Table 2. The SM parameter values \( \alpha_1/\alpha_2 \) and \( k \) used for the description of the decay of Po and At compound nuclei. They give the best fit of the excitation functions calculated with SM [7] to the \( ^{3.4}\text{He} + \text{Pb,Bi} \) data [20,21]. The \( L_{cr} \) values [23] are also shown for the comparison with those presented in Table 1.

<table>
<thead>
<tr>
<th>Projectile</th>
<th>Target</th>
<th>( \alpha_1/\alpha_2 ) (WR) [7]</th>
<th>( k )</th>
<th>( L_{cr} ) (MeV/fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{4}\text{He} + ^{208}\text{Pb} )</td>
<td>( ^{208}\text{Bi} )</td>
<td>1.0563–1.0565</td>
<td>0.85</td>
<td>28</td>
</tr>
<tr>
<td>( ^{4}\text{He} + ^{209}\text{Bi} )</td>
<td>( ^{209}\text{Bi} )</td>
<td>1.0677, 1.0670</td>
<td>1.0615</td>
<td></td>
</tr>
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</table>

The macroscopic fission barriers \( B_m \) for Po nuclei derived with the SM [7] analysis of the ER and fission cross section data obtained in the HI fusion as previously described in [14] (different color symbols). The same is also but for the result of the present analysis of the cross section data obtained in the \( ^{3.4}\text{He} + \text{Pb} \) fusion reactions [20,21] (black circles). The predictions [2,3,11,12] are shown for the comparison (the same lines and symbols as designated in Fig. 1).

In Fig. 5 the macroscopic fission barriers \( B_m \) for Po nuclei with the present analysis of the ER and fission cross section data obtained in the HI fusion as previously described in [14] (different color symbols) and the values obtained in the framework of the LSD-model calculations [12])

In Fig. 6 the macroscopic fission barriers \( B_m \) for At nuclei with the present analysis of the cross section data obtained in the \( ^{3.4}\text{He} + \text{Pb} \) fusion reactions [20,21] are shown and compared with the predictions [2,3,11,12]. The barriers are lower than any predictions (apart the values from [12]), as obtained in the case of the results of the data analysis for Fr and Ra (Fig. 1).

Note that available ER cross section data obtained in the \( ^{197}\text{Au}(^{12}\text{C},xn) \) \( ^{209–x}\text{At} \) reactions (see [24] and Refs. therein) reveal a difference in the values corresponding the factor of 5–6. Such spread of the data leads to

Figure 4. The fission cross section data obtained in the \( ^{4}\text{He} + ^{208}\text{Pb} \) reaction [20] (triangles) together with the fission excitation functions calculated in the same way as in Fig. 3 and with and without the use of \( L_{cr} \) (lines). Fusion cross sections calculated with the nuclear exponential potential [22] and those tabulated in [23] are also shown for the reference by specified lines.

Figure 5. The macroscopic fission barriers \( B_m \) for Po nuclei with the present analysis of the ER and fission cross section data obtained in the HI fusion as previously described in [14] (different color symbols). The same is also but for the result of the present analysis of the cross section data obtained in the \( ^{3.4}\text{He} + \text{Pb} \) fusion reactions [20,21] (black circles). The predictions [2,3,11,12] are shown for the comparison (the same lines and symbols as designated in Fig. 1).
the spread in the ‘adjusted $k_t$ values’ within the range of $0.5$–$1.0$, according to the present SM [7] analysis.

4. Summary

The ER and fission cross sections data for the $^{3,4}$He induced reactions leading to Po and At compound nuclei [20,21] were analysed in the framework of the statistical model (SM) approximations [7]. With the corresponding choice of parameters, SM reproduces the cross section data for evaporation of neutrons and fission rather well. The macroscopic fission barriers derived for Po and At nuclei were found to be lower than those predicted with the models [2,3,11]. The exception is the barrier values predicted by the LSD model [12], which are distinctly lower than the derived ones. The same behaviour was earlier observed for Po barriers in the region of $114 \leq N \leq 128$, as the result of the analysis of the HI fusion reaction data [14]. The barriers derived with the present study are in satisfactory agreement with those resulted in the previous analysis [14]. These findings indicate that $^{3,4}$He data can be used to verify the results of the HI fusion data analysis applying a similar approach. The derived macroscopic fission barriers (along with other SM parameters used to describe the decay of compound nuclei) can be also used for the estimates of the fusion probability in the HI reactions induced by massive projectiles, which lead to Po and At compound nuclei.

References