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STATISTICAL MODEL AND CROSS SECTIONS FOR EVAPORATION RESIDUES FORMED IN THE REACTION OF ^{22}Ne + ^{190}Os AT THE HEAVY-ION BOMBARDING ENERGY OF 6.0 — 10.0 MeV/nucleon

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Introduction

It is known, that for compound nuclei with $Z \geq 82$, created in heavy-ion fusion reactions, fission is the main decay channel, and other decay channels have a low probability even when these compound nuclei are formed at the heavy-ion bombarding energy close to the fusion barrier. This is the reason why the method of fission barrier determination based on the observation of the energy dependence of the fusion-fission cross section does not work well for these nuclei, though this method was applied successfully for measurements of fission barriers in the region of more light nuclei (see e.g. [1]). In principle, one could extend the method to heavier nuclei, however, this will require experiments of exceptional accuracy hardly possible in reality.

On the other hand, it was mentioned repeatedly (see e.g. [2]), another approach based on the analysis of production cross sections of evaporation residues may become sensitive enough and almost universal way to ascertain fission barrier values of heavy, fissile nuclei. In other words, by using this approach, one should be able to make certain conclusions about fission barriers and some other parameters essential for statistical model intended to explain the de-excitation process of heavy, fissile compound nuclei.

The real sensitivity to fission barrier values, which can be obtained in experiments realizing this approach was demonstrated in our papers [3, 4] where we analyzed formation cross sections of neutron deficient isotopes of Bi with mass numbers $187 \leq A \leq 192$, produced in complete fusion reactions with ^{40}Ca and ^{40}Ar ions. It was shown that, for these nuclei, the addition of 2 MeV to the fission barrier height ($\sim 20\,\%$ of the total barrier value) results in an increase of calculated evaporation residue cross sections by about one and half order of magnitude.

This observation one should compare with the accuracy within a factor of $1.5 - 2.0$ easily attainable for the measurements of evaporation residue cross sections. This implies that, by comparing the measured and calculated cross sections, one will be able to know, with a high accuracy, fission barrier values. In the framework of the chosen compound nucleus de-excitation model, these barrier values will be the model parameters. The possible issue as to which extend the values obtained as a result of such an analysis correspond to real barriers becomes the question of the reliability and justification of the approximations used in the model.

To answer this question is not a trivial task. It requires, as a minimum, systematic experimental investigations aimed at the creation of a sufficiently complete and detailed set of experimental data, which will be the subject of an analysis. In our earlier papers we reported some data on evaporation residue cross sections obtained from de-excitation of the compound nuclei ^{191,193,199}Bi [4, 5], ^{200,202}Po [6, 7], ^{199,205,207}At [8, 9], ^{216,218,220}Ra [10, 11], ^{217,219}Ac [12] and ^{228,230}U [13, 14] and analyzed these data in terms of their comparison with statistical model calculations. The present work is a continuation of these investigations for compound nuclei of ^{212}Ra. An additional feature of this work is that a large part of the experimental data are obtained at the compound nucleus excitation energy of more then 100 MeV. Also, for the cross section calculations use was made of the code HIVAP [15].

Experimental conditions and results

Experiments were carried out on the beam extracted from the U400 cyclotron of the Flerov Laboratory of Nuclear Reactions, JINR Dubna. Beams of ^{22}Ne with the energy of 160, 192, and 217 MeV were used. The beam intensity was limited to $2 \times 10^{11} s^{-1}$. The beam energy was varied smoothly by steps of 3-6 MeV using aluminum or titanium foils. The beam energy on the target was determined by measuring the energy of ions, scattered from the target to 30° using a Si detector. The detector was calibrated with standard α sources, and corrections for an ionization defect and effect of the detector "dead" surface layer were not considered. Errors in the estimated absolute energy values made $\pm(1.0 - 1.5)\,\%$, i.e. ± 2.0 MeV for typical energy values used in our experiments. The accu-

racy of relative energy value determination was better by a factor of 2-3, i.e. errors of relative energy values were $\pm(0.7 - 1.0)$ MeV.

Complete fusion reaction products were separated from bombarding ions and deep inelastic reaction products by the kinematic separator VASSILISSA [16, 17]. VASSILISSA is a three stage electrostatic separator with an acceptance solid angle of 15 msr for the reaction products emitted in beam direction. It separates recoil nuclei with electric stiffness within a band of $\pm 10\,\%$ in width. The recoil path time from the target to the separator focal plane makes $(1 - 3)$ μs.

The separator efficiency for the complete fusion products depends on the bombarding ion mass. For $A > 200$ compound nuclei it varies from $(2 - 3)\,\%$ to $(25 - 30)\,\%$ at the transition from bombarding ions of oxygen to argon. In these experiments, the separation efficiency was measured for each run by making use of the standard reaction ^{22}Ne(135 MeV)+$^{nat.}$W(340 μg/cm^2) and made, for different runs, the value between 3.7 % and 5.3 % depending on the separator tuning and projectile beam characteristics. We deduced the separation efficiency for the products obtained after neutron evaporation from compound nuclei from the ratios of specific α activities obtained in the separator focal plane and in a catcher foil placed just behind the target [12, 17]. The estimated efficiency values were used for calculations of the cross sections for xn and pxn reactions. For αxn reactions, the measured efficiency was reduced by a factor of 6 to take into account the broad angular distribution of corresponding reaction products. This reduction factor for αxn reaction products we found in experiments made for the reaction ^{22}Ne+^{197}Au [12], and it well coincides with the calculated value [18].

Evaporation residues were detected and their α decay energies were measured in the focal plane of the separator by a detector array [19] consisting of two wide aperture time-of-flight detectors with time resolution of 0.5 ns and an eight-strip 60×60 mm^2 Si detector having an energy resolution of ≈ 15 keV for (6-9) MeV α- particles. A preliminary calibration of the strip detector was made with a ^{226}Ra α source, and the final energy calibration was accomplished by making use of implanted α emitters, which were the products of the reactions of ^{22}Ne with W, Os and Pt targets.

Evaporation residues were identified according their α- decay energies and excitation functions. Values of α- decay branches of Po, At and Ra isotopes and isomers necessary for calculations of their cross-sections were

Table 1: Cross-sections for xn-reaction channels by the de-excitation of the ^{212}Rn compound nucleus.

E_{Ne} MeV	E^* MeV	7n[a]	8n	9n	10n	11n	12n	13n
		Cross-sections, μb						
129.5	78.0	27700	1700					
134.0	82.0	20400	4600					
138.0	85.5	12800	6300	130				
142.5	89.5	7000	7700	650	10			
148.5	95.0	3000	6000	2050	20			
151.0	97.5	2000	5100	2670	30			
155.5	101.5	1000	2700	3000	135			
161.0	106.0		1150	1900	370	3		
167.5	112.5		510	1400	520	10		
173.0	117.0		250	690	450	33		
176.0	119.5		180	470	340	39		
181.5	124.5			220	210	57		
187.0	129.5			130	140	58	2.0	
192.5	134.5			90	110	42	2.5	
199.5	141.0				100	29	3.6	
208.0	148.5					18	2.9	0.25
217.0	156.5					10	1.8	0.75

[a]contribution from the 6n-reaction channel is not subtracted.

taken from Refs. [20, 21]. For the 6.228 MeV isomer ^{202m}At the branching ratio for α-decay was assumed to be 15 % on the basis of systematics. Contribution to the count rates from the α- decay of mother nuclei was subtracted from the experimentally measured yields. We summed up the cross sections obtained for the ground and isomeric states of the same isotope. The cross-section values obtained finally as a result of the described data evaluation for the reaction channels with different specified sorts and numbers of evaporated particles are presented in Tables 1 and 2 and also are shown in Fig. 1 together with the results of HIVAP calculations. Excitation energy of the compound nuclei were determined with the use of experimental mass tables of atomic nuclei [22].

Statistical errors of the measured yields for individual evaporation residues of Rn made ± 5 %, and it was $\pm(10-15)$ % for isotopes (isomers)

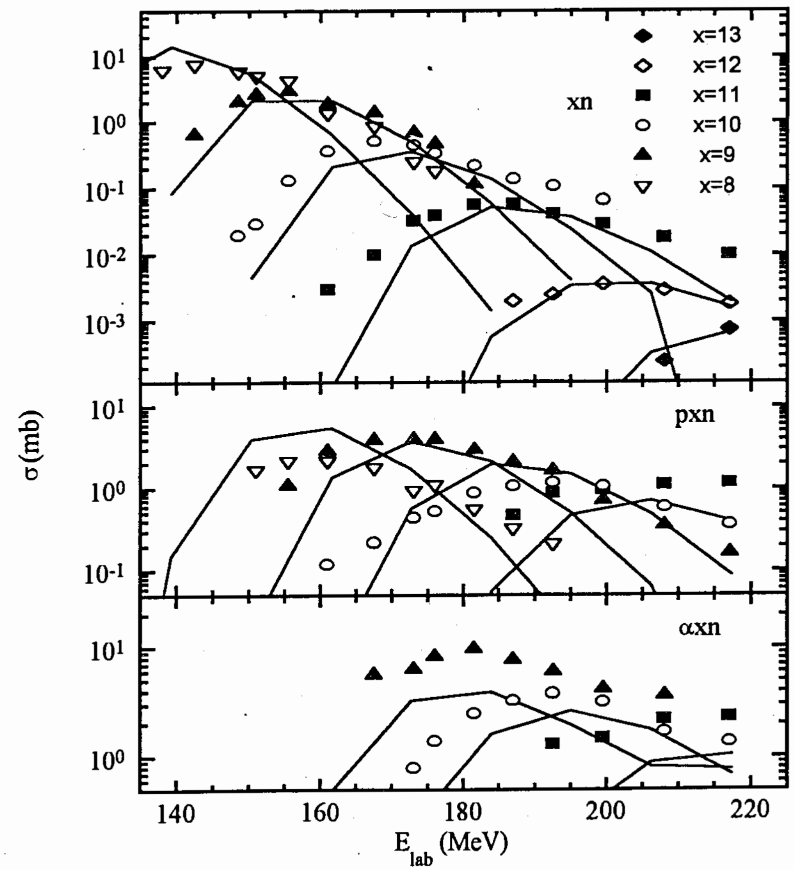

Figure 1: Excitation functions for xn, pxn, and αxn evaporation channels obtained for the reaction of ^{22}Ne+^{190}Os. Symbols show the experimental data. Calculations making use of the HIVAP code are shown with full lines.

Table 2: Cross-sections for pxn and αxn-reaction channels by the de-excitation of the ^{212}Rn compound nucleus.

E_{Ne} MeV	E^* MeV	Cross-section, mb p8n	p9n	p10n	p11n	α9n	α10n	α11n
151.0	97.5	1.7						
155.5	101.5	2.2	1.1					
161.0	106.0	2.2	2.9	0.12				
167.5	112.5	1.8	4.0	0.22		5.7		
173.0	117.0	1.0	4.0	0.44		6.3	0.8	
176.0	119.5	1.1	4.0	0.53		8.4	1.4	
181.5	124.5	0.7	3.0	0.88		9.9	2.5	
187.0	129.5	0.3	2.1	1.06	0.32	7.7	3.3	
192.5	134.5	0.2	1.6	1.18	0.90	6.0	3.8	1.3
199.5	141.0		1.2	1.07	0.95	4.2	3.2	1.5
208.0	148.5		0.6	0.59	1.10	3.6	2.2	2.2
217.0	156.5		0.3	0.36	1.17		2.1	2.3

of At and Po. Mainly, the sources of these errors were inaccuracies in accounting for the background under the isolated α peaks. For At and Po nuclei, additional errors originated from subtraction of the contributions from mother nuclei. The yield determination of ^{199}Po in the α9n reaction channel made an exclusion. This reaction product was obtained in the range of the compound nucleus excitation energy of 106 – 118 MeV. Within this range, the part of ^{199}Po formed after the α decay of ^{203}Ra varied from 100 % to 30 % of the total yield of this nucleus. Therefore, the statistical errors of the measured cross-sections of the α9n reaction varied in this energy range from $\pm$50 % to $\pm$25 %.

Errors of obtained cross sections involved also inaccuracies in measurements of the separation efficiency ($\pm$20 %), target thickness ($\pm$5 %) and beam current. Taking into account different possible systematic errors, first of all, in the beam current measurements, we assume that the real accuracy of the presented absolute cross section values makes ($\pm$40 %). The accuracy of the relative cross section values is better by a factor of two or three.

Comparison of experimental data with HIVAP code calculations and discussion

In the first part of this section we will briefly outline the main parameters, which enter into the statistical code HIVAP and will discuss our experimental data for cross sections of xn, pxn and αxn de-excitation channels of the ^{212}Rn compound nucleus. In the second part we will compare HIVAP calculations with the whole data set, which we obtained earlier for evaporation residue cross sections in the region of compound nuclei extending from Bi to U [4 - 14].

The experimental data were analyzed using the code HIVAP, where the production cross sections of evaporation residues in complete fusion reactions are calculated in the framework of the statistical model of compound nucleus de-excitation. The use of the statistical model appears to be a reasonable and necessary step in the data analysis because it imposes a minimum of requirements and assumptions. Namely, it neglects formation details of a fully equilibrated compound nucleus and assumes that different decay modes of this nucleus are defined by their statistical weights in the nucleus phase space.

Nuclear level density appears to be the most important component in statistical model calculations. In our earlier papers, the ALICE-MP code [23] was used for cross section calculations where the level density is calculated with the Fermi gas model relations modified in order to take into account the influence of shell effects on the level density parameter according to the prescriptions given by Ignatyuk [24].

The HIVAP code provides two choices for level density calculation. These are the Fermi gas model formula (without taking into account effects of the collective level density enhancement) and the expression used by Reisdorf [15] to take into account the level density dependence on the area and curvature of the nuclear surface. It appeared to us that it will be instructive to directly compare these two approaches to the level density and to see how the fission barriers extracted from the fit to the experimental cross sections are modified at the transition from one approach to another.

To make the comparison correct, we fixed all other model parameters in our calculations. In these calculations we assumed that fixed angular momentum values - 1, 1, and 3 units of $\hbar$ - are taken away from the nucleus, respectively, at the evaporation of a neutron, proton and α particle (the same assumption we made when calculations were performed with the code ALICE-MP). In the calculations making use of the Fermi gas model we adopted the ratio of asymptotical level density parameters in fission and particle evaporation channels $\tilde{a}_f/\tilde{a}_\nu = 1$. Experimental arguments in support of this choice of the $\tilde{a}_f/\tilde{a}_\nu$ value were discussed in detail in Ref. [11].

We took into account shell effects in the level density formula according to Ignatyuk [24]. The sole free parameter, which remained in our calculations was the coefficient C used for the scaling of the liquid-drop fission barrier of the studied nuclei. The total barrier was presented as a sum of the liquid-drop and shell-effect parts:

$$B_f(l) = CB_f^{LD}(l) + \Delta B_f^{Shell}.$$

Liquid-drop barriers ($B_f^{LD}(l)$) were calculated using the Cohen-Plasil-Swiatecki (CPS) model [25] of rotating charged liquid drop. Values of the shell effect barriers were taken to be equal to the differences between the liquid- drop [26] and experimental [22] masses of nuclei.

Calculated cross-section values for xn, pxn and αxn de-excitation channels of ^{212}Rn compound nuclei are compared with our experimental data in Fig. 2.

One can see from the figure that the use of any of two level-density formulae can give a good agreement with experimental cross sections for xn reactions as well as for pxn ones even if the range of the cross section variation is rather wide (four orders of magnitude). For the case of αxn reactions, the calculated cross sections are lower then the experimental data on average by a factor of two. However, taking experimental errors into account, we believe that this result is satisfactory.

The optimum values of the scaling parameter C were obtained to be 0.65 and 0.75, respectively, for the first and second choice of the level density calculation. This allows us to make the statement, that the replacement of the Fermi gas level density formula with a more sophisticated expression did not result in a significant change of the value of the liquid-drop barrier, which can be extracted from the evaporation residue cross sections. Like it was already noted for the case, when the cross sections were calculated by the ALICE-MP code, the obtained liquid-drop barriers are by about 30 % less then they are predicted by Cohen-Plasil-Swiatecki [25] or Sierk [27].

To prove the general validity of the statement made above we calculated, using the HIVAP code, the evaporation residue cross sections

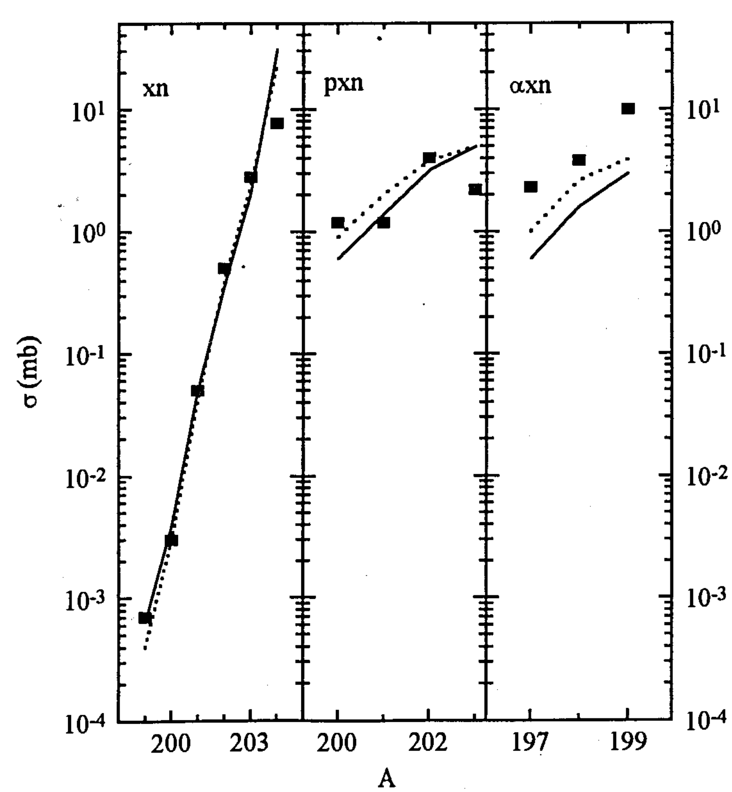

Figure 2: Maximum values of xn, pxn, and αxn cross sections. Solid squares are the experimental points, dotted and full lines show the results of the HIVAP code calculations made, respectively, with the use of the Fermi gas model and Reisdorf's version for the level density calculation.

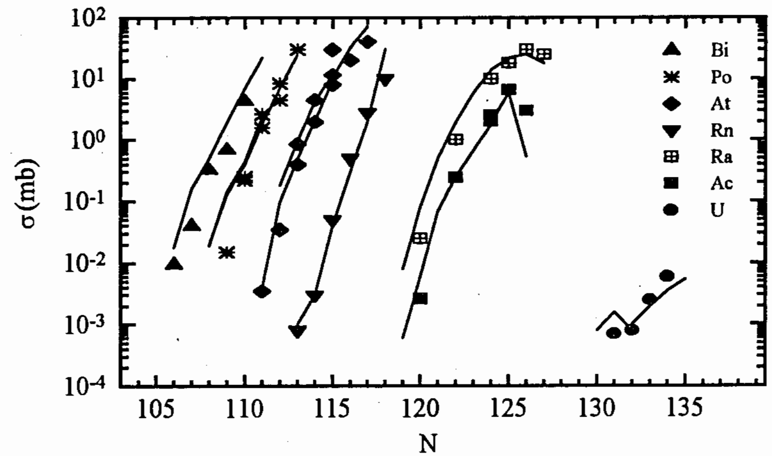

Figure 3: Maximum cross section values of xn evaporation channels for the product nuclei ranging from Bi to U. Full lines show the results of the Fermi gas model calculations with $C = (0.59 - 0.69)$. Experimental values are shown with symbols.

for the whole data set presented in our papers [4 - 14] these calculations the scaling factor C before the liquid-drop barrier again was the only free parameter, which was searched for the evaporation residues of each compound nucleus in the way similar to that outlined for ^{212}Rn. Level densities were calculated using the Fermi gas formula.

The obtained results are shown in Figs. 3 and 4. In Fig. 3 the calculated and experimental maximum cross-section values are compared for xn-reactions.

One can see that, in spite of the wide range of the data variation, the calculations reproduce well (within a factor of 2 or 3) both the relative and absolute values of the cross sections. In its turn, Fig. 4 gives a clear notion about the big differences between the fission barriers of the nuclei involved in this set of data both in the value and nature of these barriers.

Liquid-drop barriers decrease from 7.0 MeV – typical values for the neutron-deficient isotopes of bismuth – to 2.5–3.0 MeV – the barriers, which are characteristic for the neutron-deficient uranium isotopes. Shell-effect component of the barriers is close to zero in the region of neutron-deficient Bi isotopes, it grows to its maximum value of 5.0—7.0 occurring for neutron-deficient isotopes of Ra—Ac lying in the vicinity of the neu-

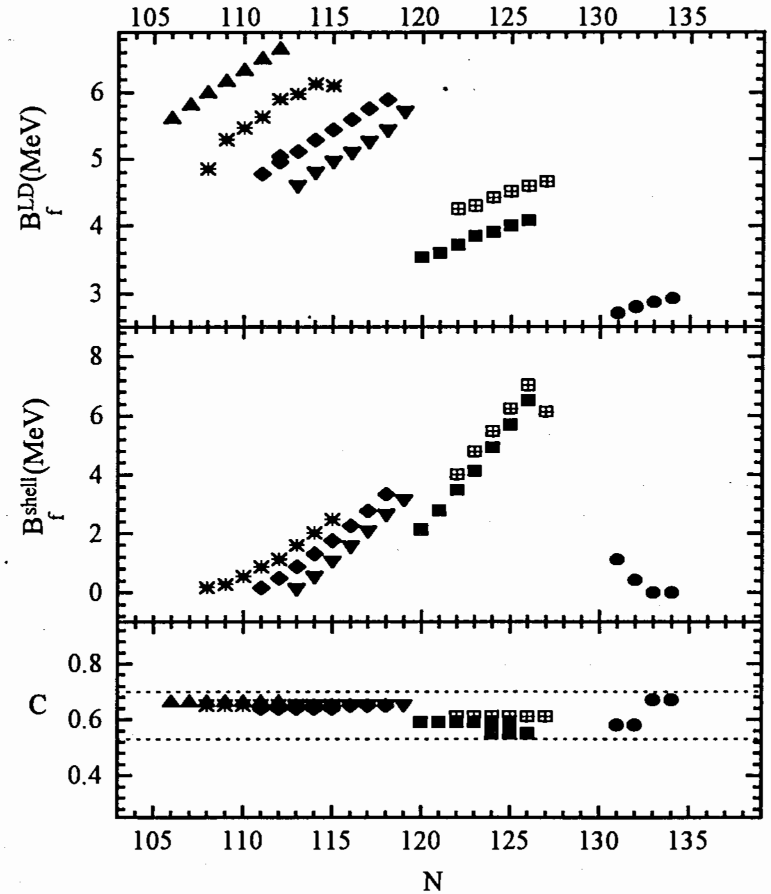

Figure 4: Values of the liquid-drop (B_f^{LD}) and shell-effect (B_f^{Shell}) components of fission barriers for nuclei that present in Fig. 3. Obtained optimum values of the scaling parameter C are shown in the bottom (for further explanations see the text).

tron magic number $N = 126$, and this component again drops to zero at the transition to neutron-deficient isotopes of U.

It is noteworthy that for the whole this region the obtained value of the sole fitting parameter C practically stays constant. Actually this value is obtained in the range of 0.55–0.68. Similar calculations making use of the second level-density formula lead to the essentially same result. The only difference was an increase of the optimum parameters C values by 0.1 for all nuclei, as it was the case for ^{212}Rn.

The results of the analysis show, that the whole set of experimental data can be well described within the framework of the statistical model of the compound nucleus de-excitation realized in the code HIVAP. Practically fixed parameters of the model – $\tilde{a}_f/\tilde{a}_\nu = 1$ and $C = 0.63 \pm 0.05$ – allow to obtain a good fit to the data points varying in a wide range. The only assumption that one should make is that the values of liquid drop fission barriers for all the nuclei emerging as evaporation residues in the considered reactions are less by $(30 - 40)\,\%$ in comparison with the values predicted by Cohen-Plasil-Swiatecki [25] or [27].

We do not exclude that, partly, this observation could be the consequence of some simplifications made in the calculations using only one free parameter – the scaling parameter C. However, the circumstance that this sole free parameter did not "wish to be free" and remained constant in a wide range of A and Z hardly can be referred to a inadequate simplification of the model used for calculations. Rather, the obtained values of this scaling parameter, which appeared to be considerably less then one are the witness that there are some general and yet not recognized reasons leading to the fissility of neutron-deficient nuclei, which is higher compared with that what was expected.

A possible alternative explanation of the disagreement between the experimental data and calculations making use of theoretical fission barriers values is the assumption about possible principal methodological errors in the way of accounting for the probability of the compound nucleus fission decay mode adopted by the statistical model.

Conclusion

Cross sections for xn, pxn, and αxn evaporation reaction channels have been measured for compound nuclei of ^{212}Rn obtained as a result of complete fusion of bombarding ions of ^{22}Ne in the projectile energy range

of $6 \div 10$ MeV/nucleon with target nuclei of ^{190}Os. A comparison between the experimental and calculated cross-section values showed that, up to the compound nucleus excitation energy of 160 MeV the statistical model of compound nucleus de-excitation well describes the experimental data.

However, as it was obtained earlier for compound nuclei produced in the excitation energy region of 40–100 MeV, the necessary condition for attaining a correct description of maximum cross-section values and excitation functions of individual reaction channels was the adoption of the value for the liquid-drop fission barrier reduced by $(30 - 40)\,\%$ as compared with the predictions of the Cohen-Plasil-Swiatecki and Sierk models. Also, it was shown that the employment of a more sophisticated approach for the nuclear level density calculation, instead of the use of the relatively simple Fermi gas formula, did not change the situation drastically.

An analysis made with employment of the code HIVAP for a large body of experimental data on evaporation residue formation cross sections (15 target – projectile combinations, which resulted in the formation of 50 individual evaporation residues) showed, that the inference, that the liquid-drop barriers are less by $(30 - 40)\,\%$ as compared with theory predictions, is universal in the sense, that it appears to be correct for all neutron-deficient nuclei in the region from Bi to U. Earlier, we came to entirely the identical conclusion from the analysis of the same data set made on the basis of the computer code ALICE-MP.

Above this, it should stressed that a correct (within a factor of 2-3) description of cross-section values in the whole region from Bi to U requires the application of *one fixed set* of main parameters of statistical model – $\tilde{a}_f/\tilde{a}_\nu = 1$ and $C = 0.63 \pm 0.05$. The cross sections are described correctly with this set of parameters for very different nuclei – these are the nuclei with vanishing shell effects as well as those, having shell-effect barriers of 5–7 MeV, which values even exceeds the liquid-drop barrier values calculated for these nuclei. This observation allows us to make the conclusion that Ignatyuk's prescription for accounting for the shell effects in the de-excitation process is a very good first order approximation in the excitation energy range extending up to $\simeq$160 MeV.

An obvious fine structure in the behavior of the scaling parameter C appearing in Fig. 4 for the evaporation residues with neutron numbers $N \simeq 126$ should be the subject of additional experiments and a detailed analysis aimed at a more correct accounting for the role of shell effects in evaporation residue cross sections obtained as a result of both "cold" and "hot" heavy-ion fusion.

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Статистическая модель и сечения образования испарительных продуктов в реакции $^{22}Ne + ^{190}Os$ при энергиях бомбардирующих ионов 6—10 МэВ/нуклон

В реакции $^{22}Ne + ^{190}Os$ измерены сечения образования испарительных продуктов в xn, pxn и αxn каналах девозбуждения составного ядра ^{212}Rn в диапазоне возбуждения от 80 до 160 МэВ. Сравнение экспериментальных данных с расчетами по статистической модели девозбуждения компаунд-ядра показало, что необходимым условием согласования экспериментальных и расчетных данных является уменьшение величин жидкокапельных барьеров деления для нейтронодефицитных изотопов Rn, At и Po на 30 ÷ 40 % по сравнению с барьерами, получаемыми в расчетах по моделям Коена—Плазила—Святецкого или Сирка. Проведенный дополнительно анализ большого массива экспериментальных данных (около 15 комбинаций мишень—частица и 50 ядер-продуктов) показал, что уменьшение жидкокапельных барьеров деления на 30 ÷ 40 % по сравнению с теоретическими предсказаниями носит универсальный характер и наблюдается для всех нейтронодефицитных изотопов в области от Bi до U.

Работа выполнена в Лаборатории ядерных реакций им.Г.Н.Флерова ОИЯИ.

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Statistical Model and Cross Sections for Evaporation Residues Formed in the Reaction of $^{22}Ne + ^{190}Os$ at the Heavy-Ion Bombarding Energy of 6.0 — 10.0 MeV/nucleon

Production cross sections were measured for the xn, pxn, and αxn de-excitation channels for the compound nuclei of ^{212}Rn formed in the excitation energy range from 80 MeV to 160 MeV in the reaction $^{22}Ne + ^{190}Os$. The comparison of the obtained experimental data and cross sections calculated using the statistical model of compound nucleus de-excitation (HIVAP code), showed that an inevitable condition for the agreement of experimental and calculated values is the assumption that the liquid drop fission barrier heights for neutron deficient nuclei of Rn, At, and Po are lower by (30 — 40) % in comparison with barriers obtained from calculations using the Cohen—Plasil—Swiatecki or Sierk models. An additional analysis of a large number of experimental data showed, that the decrease of liquid drop fission barrier values by (30 — 40) %, in comparison with the theoretical ones, has a universal character and is observed for all neutron deficient nuclei from Bi to U.

The investigation has been performed at the Flerov Laboratory of Nuclear Reactions, JINR.

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