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HOT FUSION REACTION CROSS-SECTIONS

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In the frame of the statistical theory of decay of compound nuclei we suggested a simple parametrization which allows for satisfactory reproduction of the complete set of experimental data on the cross-sections of (HI, xn) reactions for the bombarding ions lighter than $A < 40$ and for compound nuclei with $Z > 100$. We came to an observation that the value of the xn-reaction cross-section depends, besides the Γ_n / Γ_f ratios for each step of the evaporation cascade, also on the value of the «survival zone» that is determined completely by the fission barrier. The cross-sections of $4n$- and $5n$-reactions are calculated for a number of projectile-target combinations leading to the formation of evaporation residues in the region of heavy transfermium nuclides.

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

Сечение реакций горячего слияния

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В рамках статистической теории распада составных ядер предложена простая параметризация, позволившая получить хорошее описание всей совокупности имеющихся экспериментальных данных о сечениях (HI,xn)-реакций, вызываемых ионами легче аргона, для составных ядер с $Z > 100$. Показано, что величина сечения для xn-реакций в этой области ядер определяется не только отношениями испарительной и делительной ширин Γ_n / Γ_f для каждой ступени испарительного каскада, но и величиной «зоны выживаемости» в конце испарительного каскада, напрямую связанной с величиной барьера деления. Сделаны расчеты сечений $4n$- и $5n$-реакций для ряда комбинаций ион-мишень, приводящих к образованию изотопов тяжелых трансфермиевых элементов.

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During recent years, the interest to «hot» fusion reactions, using actinide targets, in which compound nuclei with excitation energy of 40-50 MeV are produced, has increased [1]. At present there is a great amount of experimental data on cross-sections of such reactions with evaporation of 4-6 neutrons leading to different isotopes of the transfermium elements up to the element 106, that allows one to carry out a systematic analysis of these data.

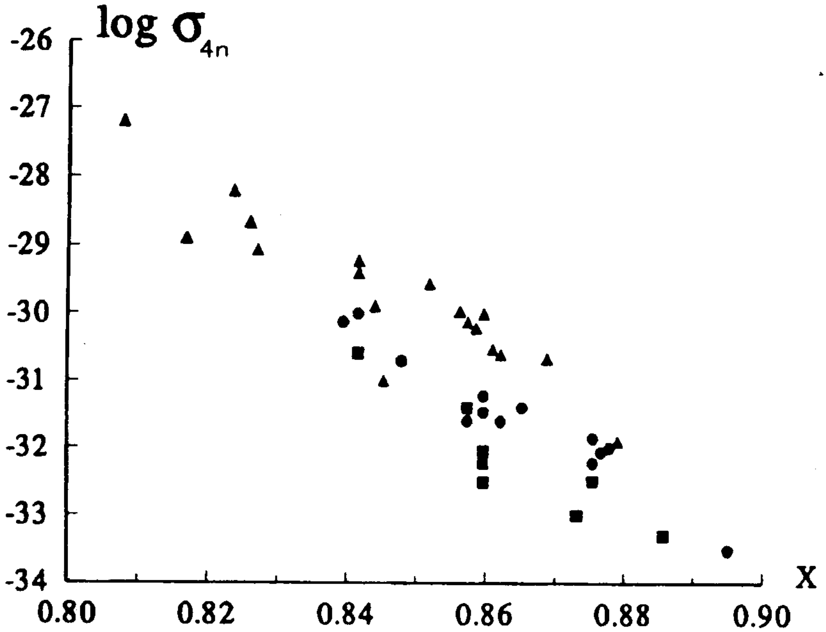

Fig.1

Figure 1 shows the values of cross-section logarithms in the maxima of excitation functions of 4n-reactions versus X — the fissility parameter of the original compound nucleus. Triangles are the values of σ_{4n}^{max} for reactions induced by B and C ions, circles — N, O, F, squares — Ne, Mg, Al. The «quiet», without any peculiarities behaviour of σ_{4n}^{max} is noteworthy. All points are sufficiently uniformly grouped around one straight line which implies an exponential dependence of σ_{4n}^{max} on X. A similar picture is observed for $5n$-reaction cross-sections (Fig.2). It is seen that for the nuclei under consideration no substantial changes occur in the xn-reaction process and all experimental data can be described using a unified algorithm. Usually one uses relations of the statistical theory of nuclear reactions for this purpose, but there exist some doubts in their validity for the fission width calculations when the fission barrier and nucleus temperature are approximately equal. At the same time, the data on the precission neutrons number obtained during the recent years indicate that fission is a slow process. This circumstance and also the exponential dependence of xn-reaction cross-sections leading to transfermium nuclei on the fissility parameter X indicate that one can try to use formalism of the statistical

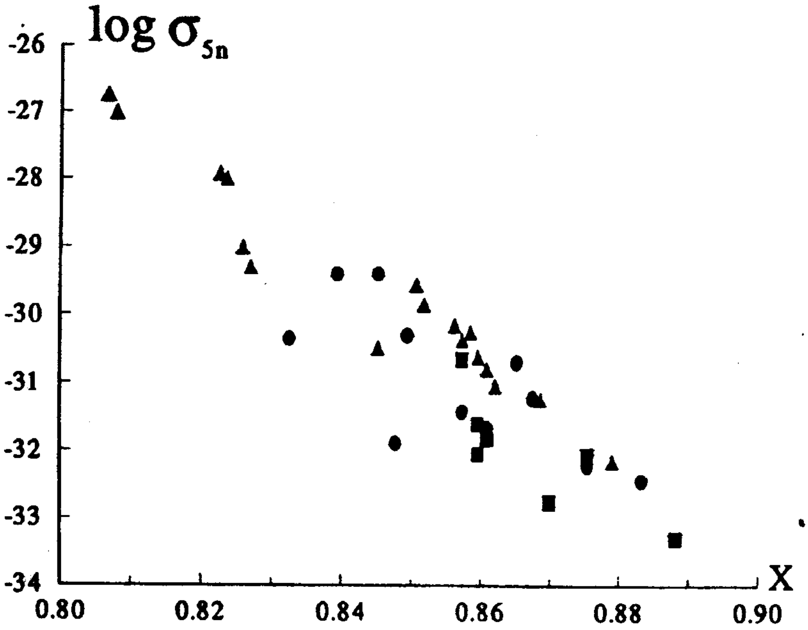

Fig.2

theory of nuclear reactions. In our calculations a statistical code based on the program ALICE was employed [2]. The cross-section of the compound nucleus formation was calculated using the formula:

$$\sigma_c = \frac{\pi}{k^2} \sum_{l=0}^{l_{cr}} \frac{2l+1}{1+\exp(2\pi\,(V_B(l) - E_{cm}) \,/\, h\,\omega_l)}, \qquad (1)$$

where $V_B(l)$ is the height of the interaction barrier and ω_l is the curvature of this barrier. The choice of parameters of the interaction potential was discussed earlier [2]. The aim of our calculations was the optimum description of the maximum values of cross-sections. More than 90% of cross-section values in their maxima are achieved at $l \ll l_{cr}$. For this reason, the results of calculations were not much sensitive to the value of l_{cr} and calculations were ended when contribution of the last partial wave to the cross-section was less than 1% of its value.

Calculations were carried out in two variants. In the first one, shell effects in evaporation and fission channels were taken into account:

$$a(E) = a\{1+[1-\exp(-0.0054E)]\Delta W/E\} \quad B_f(l) = B_f^{\mathrm{CPS}}(l)+\Delta B, \quad (2)$$

where $a = A/10$, ΔW and ΔB are the shell corrections to the masses of the residual nucleus after neutron evaporation and of the fissioning nucleus, $B_f^{\mathrm{CPS}}(l)$ is the fission barrier in the model of rotating charged drop. The ratio a_f / a_n was taken equal to 1.

In the second case the relations (2) were used also, but the values ΔW and ΔB were considered to be formal parameters. For their determination the reaction $^{248}\mathrm{U}+{}^{18}\mathrm{O}$ was used, for which excitation functions of the reactions from $4n$ to $8n$ were measured with a good accuracy. The best fit was obtained with $\Delta W = 0$ and $\Delta B = 1.1$. These values of parameters were fixed and calculations for all reactions, for which experimental data exist, were performed with them. In both variants of calculation a good fit was obtained. We consider the second variant which is more simple and more convenient for extrapolation. The results are presented in Fig.3, where there is shown a logarithm of the ratios of calculated and experimental values of cross-sections in maxima of excitation functions for reactions $4n$, $5n$ and 6n versus fissility parameter X. Dashed lines limit interval $-0.6 < \log(\sigma_{\mathrm{cal}}/\sigma_{\mathrm{exp}}) < 0.6$, i.e., for the points lying between these lines $1/4 < \sigma_{\mathrm{cal}}/\sigma_{\mathrm{exp}} < 4$. From Fig.3 one can see that overwhelming majority of the points are within this interval.

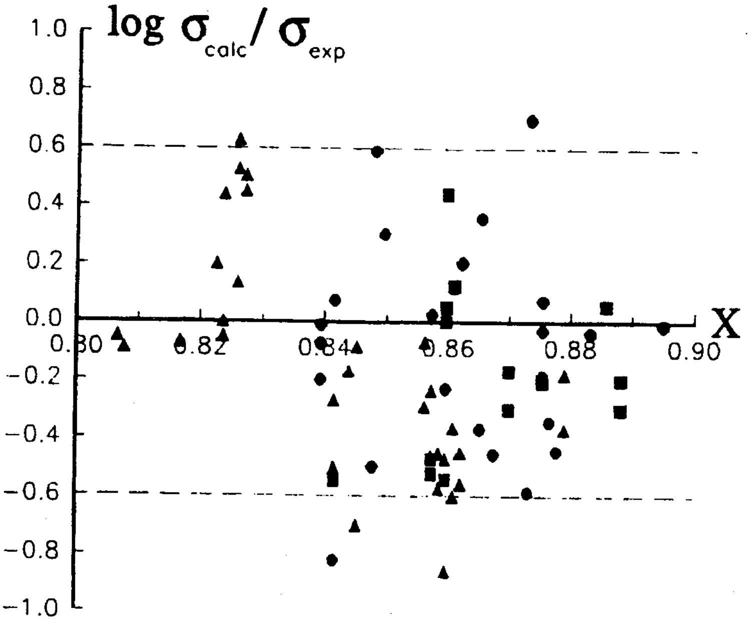

Fig.3

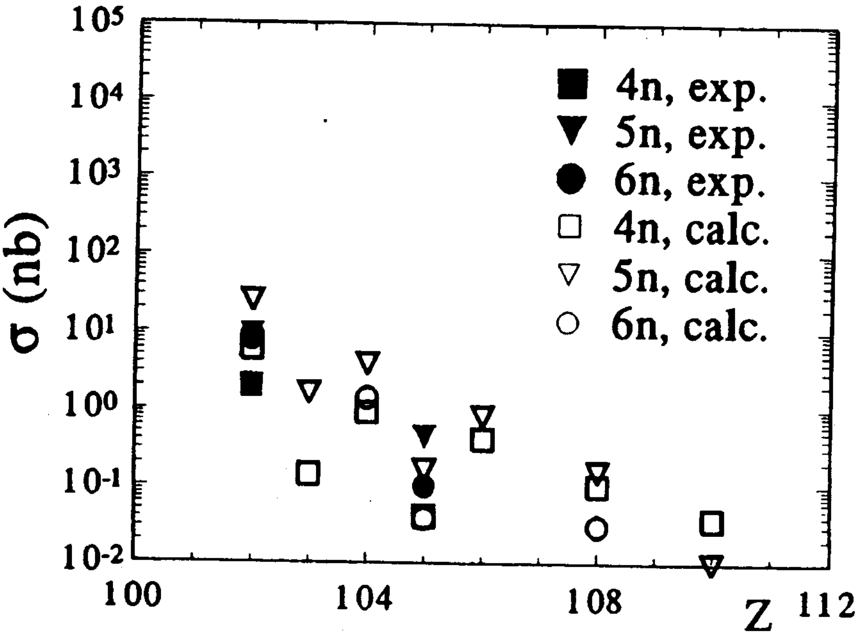

Fig. 4

One must note that the fission barriers of transfermium nuclei B_f are substantially smaller than their neutron binding energies and therefore after neutron cascade a nucleus can be found with high probability with an excitation energy within interval B_n — B_f and it undergoes fission. Only those nuclei reliably survive that after neutron cascade have the excitation energy smaller than B_f. Calculations show that this factor reduces yield of heavy nuclei by several orders of magnitude and that the value of $\langle \Gamma_n / \Gamma_f \rangle$ ratio is smoothly varying in the transfermium region and ranges near 0.1. This result qualitatively differs from the generally accepted opinion that the ratio σ_{xn}/σ_c is completely determined by $\langle \Gamma_n / \Gamma_f \rangle$ value which for heavy nuclei is of the order of 0.01.

A good agreement of calculation results and experimental data for reactions induced by Mg and Al, in which isotopes of the elements 102 and 105 were produced, is exemplified by Fig.4. This agreement indicates that there are no sensible limitations in fusion for this ions. Some estimates of production cross-sections of several isotopes of the elements 107—110 in maxima of excitation functions for 4*n*-and 5*n*-channels are listed in the table.

Table

Reaction	E_l (MeV)	4*n* E^* (MeV)	σ (pb)
^{243}Am+^{26}Mg	138	42.9	110
^{249}Cf+^{22}Ne	118	41.2	120
^{248}Cm+^{26}Mg	138	42.4	110
^{248}Cm+^{27}Al	150	46.9	10
^{242}Pu+^{36}S	187	41.2	90
^{242}Pu+^{34}S	185	44.5	14
^{249}Cf+^{26}Mg	144	42.3	37

Reaction	E_l (MeV)	5*n* E^* (MeV)	σ (pb)
^{243}Am+^{26}Mg	146	50.1	89
^{249}Cf+^{22}Ne	128	50.4	58
^{248}Cm+^{26}Mg	146	49.6	150
^{248}Cm+^{27}Al	154	50.5	33
^{242}Pu+^{36}S	196	49.0	25
^{242}Pu+^{34}S	193	51.5	10
^{249}Cf+^{26}Mg	154	51.3	10

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