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NEUTRON-TO-TOTAL WIDTH RATIOS FOR HIGHLY EXCITED TRANSCURIUM COMPOUND NUCLEI*

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1 Introduction

In our recent study new data on production cross sections of isotopes of elements 105 and 102 formed in asymmetric (HI,5-6n)-reactions were obtained [1, 2]. Comparing these results with the data on "cold" fusion reactions (exploiting Bi and Pb targets) leading to the same final products [3, 4] (see Fig. 1) one could make a qualitative conclusion that fission does not play decisive role in their formation, at least, at the first steps of deexcitation process. The subbarrier nature of the reactions leading to the isotopes of the element 105 occurring in the case of cold fusion $^{50}Ti+^{209}Bi$ and large number of deexcitation steps for the hot fusion reactions $^{27}Al+^{236}U$ and $^{31}P+^{232}Th$ made quantitative conclusions difficult. As for the production of $^{252}102$, only a crude estimation of $<\Gamma_n/\Gamma_{tot}>\simeq 0.5$ was made [2] on the basis of the data of two different experiments [2, 4] where data on 6n and 4n reactions were obtained.

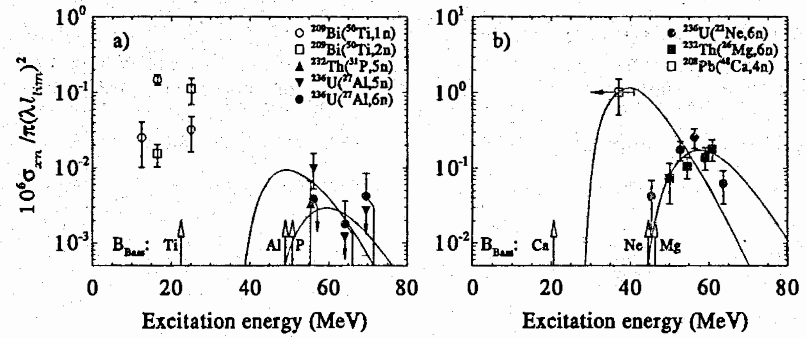

Fig. 1. Reduced cross sections for reactions leading to evaporation residues: $^{258,257}105$ — (a) and $^{252}102$ — (b). Data for "cold" fusion reactions [3,4] (open symbols) and those obtained in our experiments [1,2] (closed symbols) are presented. Fusion barriers [5] are shown by the vertical arrows. Curves represent the shape of the excitation functions fitted to the experimental points (see text below).

In this work we present the data on production cross section for the $^{252}102$ nuclide formed in the reaction $^{238}U(^{22}Ne,8n)$. Having the result for other reactions leading to the same nuclide [2] we extract the $<\Gamma_n/\Gamma_{tot}>$ values for the first two steps of the deexcitation cascade of the highly excited compound nucleus. A comparative analysis of these ratios for Z≤102 excited nuclei is presented and their excitation energy dependencies are obtained and discussed.

2 Experiment and results

Experiments were carried out on the beam of the U400 cyclotron of the FLNR, JINR using the recoil separator VASSILISSA [6]. The average beam intensity of ^{22}Ne ions was about 1.5 pμA. The isotopically enriched (99.99%) target of ^{238}U of 0.52±0.06 mg/cm^2 thickness was mounted on a rotating target wheel. The separation efficiency for evaporation residues (ER) was carefully measured in every run for the test reaction ^{nat}W(^{22}Ne,xn). The obtained value – ϵ^W_{exp} was compared with the result of a calculation – ϵ^W_c [7] and it showed a rather good agreement with the last one. Finally the adopted efficiency for the investigated reactions ^{238}U(^{22}Ne,xn) was obtained with the relation $\epsilon^U_{exp} = \epsilon^W_{exp} \cdot \epsilon^U_{calc}/\epsilon^W_{calc}$. Conditions of experiments are presented in Table 1.

Table 1. Experimental conditions for cross section measurements in the ^{238}U(^{22}Ne,xn)-reactions.

E$_{lab}$(MeV)	Ion dose($\times 10^{17}$)	ϵ^W_{exp}(%)
119	2.5	2.4
143	11.8	4.4
153	4.3	3.7

Table 2. Characteristics of mother–daughter $\alpha - \alpha$ correlated events observed at E$_{lab}$=143 MeV.

E$^m_\alpha$ (MeV)	E$^d_\alpha$ (MeV)	t$_d$ (s)
8.40	7.85	13.0
8.33	7.86	38.7

The silicon detector array installed in the focal plane of the separator allowed a reliable identification of the $^{252-256}$102 nuclides through α decay energies of these nuclides and their daughters when the production cross sections exceeded 1 nb. Fig. 2a presents the obtained α-spectrum at the beam energy of 119 MeV. At higher energies the main identified α-line in the α energy region of interest (7–9 MeV) resulted from the products of ^{22}Ne reactions occurring on lead impurities contained in the target. Therefore, we searched for $\alpha - \alpha$ mother-daughter time and energy correlations in order to identify the 8n-reaction product, i.e. ^{252}102. The characteristics of such events identified as $^{252}102 \rightarrow ^{248}$Fm decays are presented in Table 2. Ten spontaneous fission events were detected between the beam pulses at the beam energy of 143 MeV. The yield of these events corresponds to the (^{22}Ne,p3n) reaction cross section measured earlier [8]. In Fig. 2b the obtained ^{238}U(^{22}Ne,xn)$^{260-x}$102 reaction cross sections are presented together with the data obtained earlier [9].

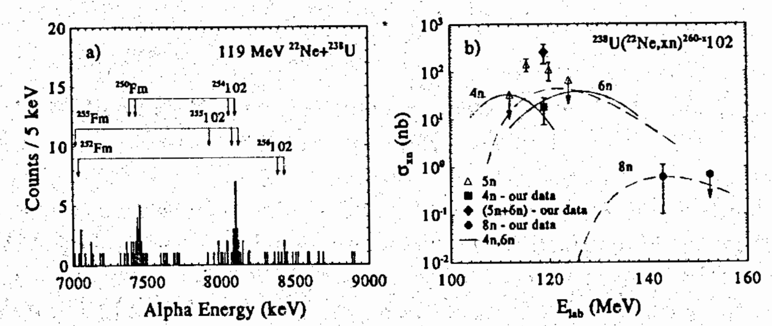

Fig. 2. Alpha spectrum obtained in the separator focal plane at the ^{22}Ne$_{lab}$=119 MeV — (a), and b) — cross section values obtained in the present work (filled symbols) along with the earlier data for the (4–6)n reactions (solid lines and open triangles [9]. Excitation functions fitted to the experimental points are shown by dashed lines (see text below).

3 $<\Gamma_n/\Gamma_{tot}>$ derived from (HI,xn)-reaction data

We proceeded from a general formula for calculation of the production cross section for a fissile nucleus formed in a (HI,xn)-reaction [9, 10]:

$$\sigma_{xn}(E) = \pi\lambda^2 \sum_{l=1}^{l_{max}} (2l+1) T_l(E) P_{x,l}(E^*) \prod_{i=1}^{x} \frac{\Gamma_n}{\Gamma_{tot}}(E^*, l). \qquad (1)$$

For the case of dominating fission decay of the compound nucleus and with some assumptions [11, 12], one can come from eq.(1) to the approximated form:

$$\sigma_{xn}(E) \simeq \frac{\pi\lambda^2 l^2_{lim} P_x(E^*)}{1 + \exp\left[2\pi(E_B - E)/\hbar\omega\right]} \prod_{i=1}^{x} \frac{\Gamma_n}{\Gamma_{tot}}(E^*) \text{ with } l^2_{lim} = \frac{2T/\hbar^2}{1/J_0 - 1/J_{sp}}, \qquad (2)$$

where E_B and $\hbar\omega$ are the entrance-channel fusion barrier parameters, T is the nuclear temperature and J_0 and J_{sp} are, respectively, the moments of inertia for sphere and for the nucleus at the fission saddle. In the case when two reactions leading, as a result of xn and $(x+y)n$ evaporation, to the same final product are considered at the ion bombarding energy well above Coulomb barrier ($E \gg E_B$) the ratio of the cross sections gives us the simple estimation of the $<\Gamma_n/\Gamma_{tot}>$ value averaged over the first y steps of the compound nucleus deexcitation cascade:

$$\frac{\sigma_{(x+y)n}}{\sigma_{xn}} \simeq \frac{\lambda^2_{x+y} P_{x+y}(E^*_{x+y}) < \Gamma_n/\Gamma_{tot} >^y}{\lambda^2_x P_x(E^*_x)}, \qquad (3)$$

where λ is the de Broglie wavelength and $P_x(E^*)$ is the probability for the emission of exactly x neutrons. Here we consider mainly the cases with y = 1,2.

Following [13] we used the Poisson distribution for estimating $P_x(E^*)$. By fitting the experimental excitation functions for (HI,xn)-reactions in the region of the transcurium nuclei we estimated the mean value of the energy associated with the evaporation of one neutron ϵ=2.92 MeV. Evaporation reactions with $x \geq 5$ were considered at fitting to exclude the Coulomb barrier influence. The following form was fitted:

$$\sigma^{fit}_{xn}(E^*) = \frac{a\pi\lambda^2}{x!}\left(\frac{E^* - \sum^x_{i=1} B^i_n}{\epsilon}\right)^x \exp\left[-\left(\frac{E^* - \sum^x_{i=1} B^i_n}{\epsilon}\right)\right], \qquad (4)$$

where a and ϵ are the fitting parameters.

In application of eq.(3) to the experimental data we used the approximated values of cross sections at the maxima of excitation functions fitted by eq.(4) with ϵ=2.92 MeV. The obtained $<\Gamma_n/\Gamma_{tot}>$ values are shown in Fig. 3. The following experimental results were used for the $<\Gamma_n/\Gamma_{tot}>$ estimations: 8n and 6n evaporation reactions for the production of ^{242}Cf [14] and ^{248}Fm [9, 15, 16], 7n and 6n reactions for ^{250}Md [9, 17], 8n (the present data) and 6n reaction for ^{252}102 [2]. All the results were obtained for the compound nucleus excitation energy range of 60–80 MeV. Using the parameters given in Table 3 statistical calculations of Γ_n/Γ_f [18] were also performed. We converted the calculated Γ_n/Γ_f values into the Γ_n/Γ_{tot} ratios using the expression: $\Gamma_n/\Gamma_{tot} = (\Gamma_n/\Gamma_f)/(1+\Gamma_n/\Gamma_f)$.

To obtain the energy dependence of the Γ_n/Γ_{tot} ratio throughout an evaporation cascade, i.e. to extrapolate it to the excitation energy corresponding to the xn evaporation reactions, where x <5, fusion barrier parameters in eq.(2) were extracted from the available experimental data relevant to this region. We analyzed: a) excitation functions for (HI,xn) reactions; b) energy dependencies for the total ER production cross-section, i.e. $\Sigma\sigma_{xn}(E^*)$, with the use of the proposed earlier approach [12]; c) excitation functions for (HI,fission)-reactions [24, 25, 26] with fitting barrier parameters in the Wong formula [23]. We estimated the accuracy of the calculated reduction factors due to the fusion barrier in eq.(2) to be within a factor of 2. For the lowest excitation energy corresponding to the 3n-reaction for the ^{242}Cf ER [14] and to the 2n-reaction for the ^{252}102 ER [4] we estimated Γ_n/Γ_{tot} from the relation:

$$\sigma_{xn}(E^*) = \sigma_{CN}(E^*) P_{xn}(E^*) < \Gamma_n/\Gamma_{tot} >^x \qquad (5)$$

The main uncertainty in the use of eq.(5) arises from a very sharp variation of $\sigma_{CN}(E^*)$ at subbarrier energies. We estimated these uncertainties within factors of 3 and 5, respectively, for the reactions ^{48}Ca+^{206}Pb and ^{12}C+^{233}U. The obtained $<\Gamma_n/\Gamma_{tot}>$ values for the nuclei involved in the deexcitation chains of the ^{250}Cf and ^{260}102 compound nuclei are shown in Fig. 4.

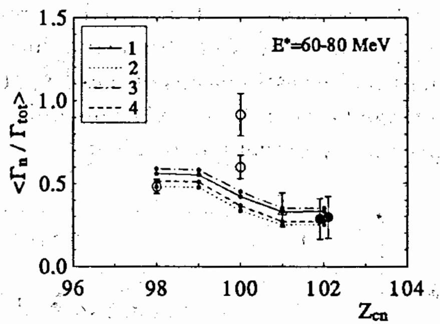

Fig. 3. $<\Gamma_n/\Gamma_{tot}>$ ratios from experimental data (symbols) and statistical model calculations (points connected with lines). Different variants of calculation are presented in Table 3.

Table 3. Different variants of the Γ_n/Γ_{tot} calculations assuming $a_n = a_f = \tilde{a}$

Variant	$a(A)$	B_f	B_n
1	[19]	[20]	[22]
2	A/10		
3	[19]	[21]	
4	A/10		

4 Discussion and conclusions

One can see from Fig. 4 that we obtained the ratios $<\Gamma_n/\Gamma_{tot}>$= 0.3–0.6 at the compound nucleus excitation energy E* > 40 MeV. These values exceed those ones extracted earlier with the use of other approach

($< \Gamma_n/\Gamma_{tot} >$=0.1–0.3) [19]. A detailed comparison of two used approaches should be done in order to discuss the differences in obtained values. We would only like to underline the fact that our estimations of the $< \Gamma_n/\Gamma_{tot} >$ ratios at $E^* > 60$ MeV are made on the basis of direct experimental results for 6n and 8n reactions and are practically model independent.

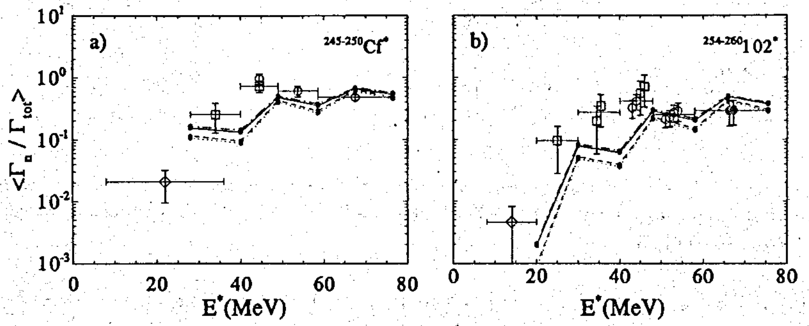

Fig. 4. $< \Gamma_n/\Gamma_{tot} >$ ratio for the nuclei involved into the deexcitation chains of $^{245-250}$Cf* leading to ^{242}Cf — a), and $^{254-260}$102* leading to ^{252}102 — b). In the left panel different symbols denote different ways of estimating barrierless cross-sections at subbarrier energies for the U(^{12}C,xn) reactions. In the right panel symbols denote different reactions involved in the analysis: circles are for the ^{22}Ne [27] and ^{12,13}C [28] induced reactions, and squares — for ^{48}Ca [4] ones. Results of calculation are obtained in the same way as in Fig. 3.

Using the obtained $< \Gamma_n/\Gamma_{tot} >$ ratios one can estimate neutron multiplicities over the neutron evaporation cascade leading to the final heavy nucleus. The estimations give the numbers ~1 for ^{250}Cf and ~0.5 for ^{260}102 compound nuclei at the highest excitation energy. The neutron-detection data gave the value $\nu_{pre} \simeq 3$ at the same excitation energy of ^{250}Cf [29]. From this observation we deduce that about two neutrons are emitted during the descent from the saddle to scission point.

From the present analysis one can conclude that the obtained values of $< \Gamma_n/\Gamma_{tot} >$ at high excitation energies are in a reasonable agreement with statistical calculations and the main losses in the yields of transcurium ER formed in heavy ion "hot" fusion reactions arise at the final steps of the deexcitation cascade.

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