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Formation cross sections of neutron deficient polonium isotopes in asymmetric and symmetrical heavy ion fusion

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Excitation functions are measured for the fusion reactions $^{27}Al+^{175}Lu$ and $^{31}P+^{169}Tm$ leading to the isotopes $^{192-198}Po$. A comparison to the data for the reactions ^{100}Mo + $^{92-100}Mo$ shows that characteristics of the compound nucleus evaporation do not depend on the bombarding ion mass in the whole range of the entrance channel asymmetry up to the fully symmetrical systems. It is also shown that a satisfactory description of the experimental data is possible in the frame of the statistical deexcitation model only at an assumption involving, in comparison to theory predictions, a considerable reduction of macroscopic fission barriers for neutron-deficient isotopes of Bi.

1. INTRODUCTION AND EXPERIMENT

In our earlier papers [1,2] data were reported about the formation cross-sections of neutron-deficient nuclides $^{196-203}At$ and $^{187-193}Bi$ produced in fusion reactions of A≤40 heavy ions. An interesting result of these investigations was the conclusion that the decrease of macroscopic fission barriers is considerably steeper at the transition from At to Bi than it is predicted by theory. In this work we continue the investigation for the Po isotopes. Earlier, two groups measured the formation cross sections for neutron-deficient Po isotopes in fusion reactions with bombarding ions of ^{40}Ar, ^{74}Kr [3] and ^{100}Mo [4]. The possibility to make a direct comparison of the cross section regularity for the same evaporation residues (ER) produced in the reactions with so different asymmetry was an additional argument for this work.

Experiments were carried out on the beam of the U-400 cyclotron making use of the recoil separator VASSILISSA [5]. Beams of ^{27}Al and ^{31}P bombarding ions with the initial energies of 178 and 220 MeV, respectively, were used in the experiments. Reaction products were identified according their α decay energy and excitation functions. Errors of the measured absolute cross-section values did not exceed 50 %, and the accuracy of relative results was better than 25 %. A detailed description of the experiments and their data is presented in Ref. [6]. In this paper we concentrate our attention on main results and conclusions.

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2. $^{31}P+^{169}Tm$ REACTION

A comparative analysis of cross sections for the xn evaporation channel of the compound nucleus ^{200}Po formed in the reactions $^{84}Kr+^{116}Cd$ and $^{40}Ar+^{160}Dy$ was made earlier [3]. The authors [3] showed that, for both reactions, shapes of excitation curves and their positions on the scale of the compound nucleus excitation energy well coincide, and the ratio of the cross sections is close to the ratio of reduced wave lengths at the entrance channels of two reactions. Data on the formation of Po isotopes in the reaction $^{100}Mo+^{100}Mo$ recently published in Ref. [4] together with our data for the reaction $^{31}P+^{169}Tm$ allow us to make such an analysis for two reactions of an extreme variation of mass asymmetry at the entrance channel (see Figures 1 and 2). One can see from Figure 1 that the relative tendencies of cross sections are practically the same for two reactions above the ^{200}Po excitation energy $E^* \geq 50$ MeV. The ratio $\sum\sigma_{xn}(P)/\sum\sigma_{xn}(Mo) = 3.3 \pm 0.5$ well correlates with the ratio of reduced wave lengths $\pi\lambda_P^2/\pi\lambda_{Mo}^2 = 3.3 - 3.1$. Such an observation is considered usually as an evidence that only a certain part of lower momentum partial waves contribute to the formation of ER, and the mean angular momentum value of those states remains constant for different mass of bombarding ions. It is evident from Figure 2 that the shapes and positions of different evaporation channels well coincide in excitation energy scale of ^{200}Po. This proves that the angular momentum distribution of the excited states of ^{200}Po participating in the yield of ER does not vary with the mass of bombarding ion up to the full entrance channel symmetry.

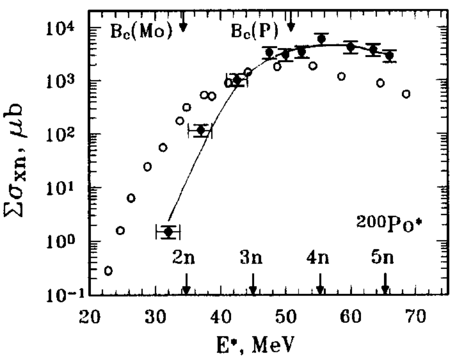

Figure 1. Total xn reaction cross section ($\sum\sigma_{xn}$) as a function of the CN excitation energy (E^*) for ^{200}Po CN formed in the reactions $^{100}Mo+^{100}Mo$ (o) and $^{31}P+^{169}Tm$ (•). Vertical arrows drawn below show positions of cross section maximums.

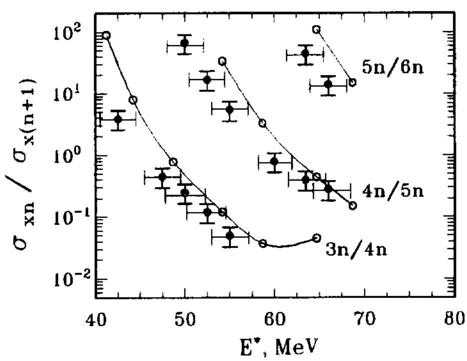

Figure 2. Ratios $\sigma_{xn}/\sigma_{(x+1)n}$ for ^{200}Po CN formed in the reactions $^{100}Mo+^{100}Mo$ (o) and $^{31}P+^{169}Tm$ (•).

3. $^{27}Al+^{175}Lu$ REACTION

Maximum formation cross sections of Po isotopes, which we obtained in this reaction are shown in Figure 3 together with similar data [4] for the reactions $^{100}Mo+^{92-100}Mo$. One can see that, up to ^{192}Po, cross sections obtained with Mo ions are equal to or less than those obtained in the reaction $^{27}Al+^{175}Lu$, in spite of the fact that the number of evaporated neutrons is considerably larger for the last reaction. This is caused by two reasons. Firstly, there is a considerable reduction of the fusion probability of Mo ions near Coulomb barrier. The second reason is the large value of neutron evaporation width at high excitation energy of Po nuclei, so that $\Gamma_n/\Gamma_{total} \simeq 1$ at $E^* \geq 40$ MeV. This observation makes one confident that the cross sections depend, to a large extend, on the fissility of final products of the compound-nucleus evaporation cascade, i.e., on their fission barriers.

We extracted the data on fission barriers by fitting our calculations, based on a modified version of the code ALICE, to the experimental maximum cross-sections. Details of the calculations are described elsewhere [1,7,8]. Calculations were carried out taking two different assumptions: 1) we neglected the shell-effect terms in fission barriers and the influence of shell effects on the level-density parameter assuming their rapid disappearance in exited nuclei, 2) ground-state shell corrections were added to the liquid-drop fission barriers, and the level-density parameter was modified following the prescription of Ref. [9]. Earlier an assumption similar to 1) was made by the authors of Ref. [12]. In both approaches, only one free parameter was left for the fit. This was the factor C on which the liquid-drop barrier was multiplied. In Figure 4a ratios of calculated to experimental cross sections $\sigma_{xn}^{calc}/\sigma_{xn}^{exp}$ are shown for the reaction ^{27}Al+^{175}Lu (x=4–10). Calculations yielded the values C=0.83 and 0.73, correspondingly, taking the first and the second assumptions. The obtained agreement is satisfactory for both cases. Such a behavior of the scaling parameter C correlates well with the observations to which we came earlier when obtained similar values of C for isotopes of At [1] and Fr–Ac [8], where the maximum ground-state shell effects amount to 5–6 MeV. Figure 4b shows the same ratios obtained for the reaction ^{40}Ar+^{165}Ho (x=4–9). Here we came to C=0.86 and 0.73 with the same assumptions.

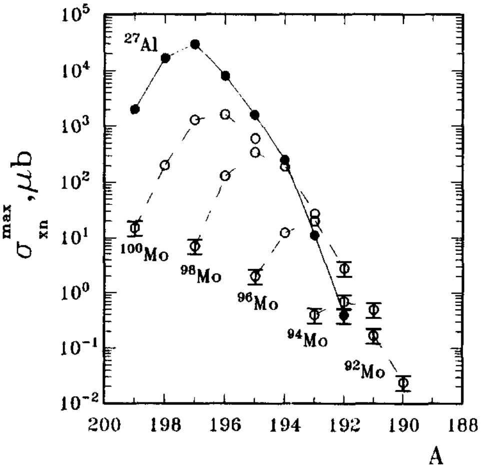

Figure 3. Maximum formation cross sections of Po isotopes in the reactions ^{27}Al+^{175}Lu (•) and ^{100}Mo+$^{92-100}$Mo (o).

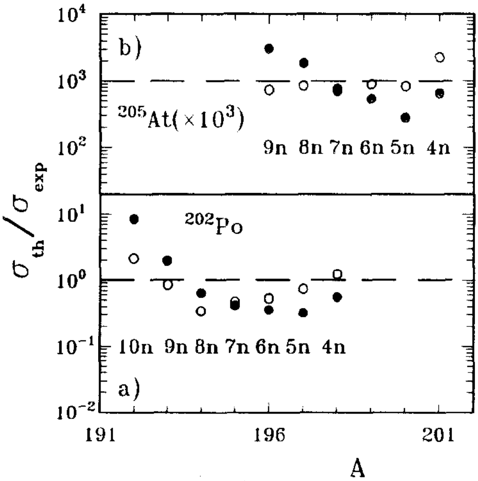

Figure 4. Values of $\sigma_{xn}^{calc}/\sigma_{xn}^{exp}$ obtained at maximum yields of Po isotopes. Closed and open circles are drawn with the assumptions 1) and 2), respectively (see text). a) reaction ^{27}Al+^{175}Lu, b) reaction ^{40}Ar+^{165}Ho (x=4–9).

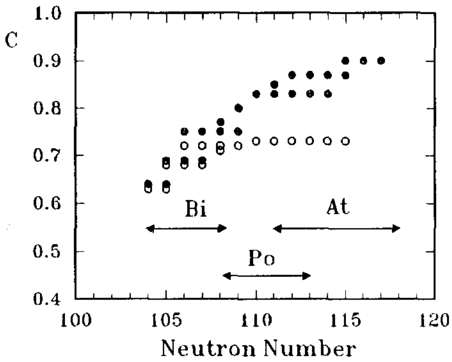

Figure 5. Derived value of the scaling factor C as a function of the neutron number. Results obtained taking assumption 1) and 2) (see text) are presented by closed and open circles, respectively.

Considering these observations one could come to a conclusion that the experimental cross section patterns are described satisfactory with both above assumptions. However, the complete data set presented in this work and in Refs. [1,2] allows to see the essential difference between results emerging from these two disparate assumptions. A steep variation of the macroscopic fission barrier occurring at the transition between neutron-deficient isotopes of At and Bi follows from the first assumption (see Fig. 5). The second assumption yields, for the whole range of At, Po and Bi isotopes, the macroscopic barriers, which are by a factor of 0.7 less than the theoretical liquid-drop barriers. This last inference appears to be more realistic. We note that earlier, the authors of Ref. [10] showed that there is a need to introduce a reduction factor of 0.6–0.7 to the liquid-drop barriers of some nuclei.

In conclusion, we like to say that a consistent statistical-model description of fusion–evaporation reactions yields a considerable reduction factor for the macroscopic fission barriers of neutron-deficient Bi–At nuclides. One possible action following this finding could be the search of a new isotopic spin dependence for the liquid-drop barrier [11].

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