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ANISOTROPY OF FISSION FRAGMENTS FOR THE REACTION $^{16}O + ^{208}Pb$

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The cross section and angular distributions of fission fragments have been measured for the compound nucleus ^{224}Th produced in the reaction $^{16}O + ^{208}Pb$ at four energy values in the range from 5 to 15 MeV below the fusion barrier calculated in terms of the Bass model. The performed measurements allowed one for the first time to obtain data for the region of interaction of heavy ions with nuclei characterized by the cross section being by 8 orders of magnitude lower than the geometric cross section. It can be seen that at the energy of oxygen ions of up to $E_{\rm lab} \leq 82$ MeV, account should be taken of the contribution made by the lowest vibration states of interacting partners. The measured angular distributions of fission fragments are in agreement with the calculations performed within the framework of the standard statistic transition state model for the saddle point. The data do not support the hypothesis that deep-subbarrier reactions are characterized by fission fragments showing anomalously high anisotropy. However in the investigated energy range there is a plateau characterized by the relation $W(180°)/W(90°) = 1.2$ in the angular anisotropy of fission fragments. This implies that the available angular packet of harmonics, which govern the production cross section of a compound nucleus, is approximately the same.

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

Анизотропия осколков деления в реакции $^{16}O + ^{208}Pb$

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Измерено сечение деления и угловые распределения осколков деления компаунд-ядра ^{224}Th, образованного в реакции $^{16}O + ^{208}Pb$, в четырех точках по энергии в интервале от 5 до 15 МэВ ниже басс-барьера слияния ядер. Проведенные измерения позволили впервые получить данные, характеризующиеся сечением на 8 порядков величины меньше, чем геометрическое сечение взаимодействия ядер. Показано, что для энергий ионов кислорода вплоть до $E_{\rm lab} \leq 82$ МэВ необходимо при расчете сечений учитывать вклад нижайших вибрационных уровней взаимодействующих ядер. Измеренные угловые распределения осколков деления находятся в согласии с результатами расчета в рамках стандартной статистической модели переходного состояния для седловой точки. Данные не поддерживают гипотезу о том, что глубокоподбарьерные реакции характеризуются аномально высокой угловой анизотропией осколков деления. Однако в исследуемой области энергий наблюдается плато, характеризующееся величиной ≈ 1,2 для угловой анизотропии осколков деления. Это указывает на то, что во всей подбарьерной области энергий пакет угловых гармоник, дающий основной вклад в образование компаунд-ядра, примерно постоянен.

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Introduction

A great number of experimental data obtained in recent years on subbarier fusion cross sections of heavy ions with a wide range of *A* and *Z* compound nuclei have stimulated an extensive discussion on the mechanism of the subbarrier reaction enhancement, on quantum effects and correlation between the dynamics of the process and nuclear structure of interacting nuclei. For the explanation of the substantial enhancement of the subbarrier reaction cross sections, different models have been developed and widely used. They take into consideration not only static deformation of nuclei, but also the possibility of weak fluctuation of the nuclear surface in the interaction process, the possibility of the vibrational states excitation and, finally, the influence of the nucleon transfer channels on the fusion probability. In addition, a number of experiments gave indication that compound nuclei produced at energies close to the interaction barrier (in particular, in the reactions $^{16}O+^{208}Pb$ [1] and $^{12}C+^{232}Th$ [2]) fission are showing anomalously high angular anisotropy of the fission fragments. It was hypothesized that subbarrier reactions should be likely to show anomalously high angular anisotropy, and possible mechanisms, responsible for the phenomenon, were suggested [3,4]. Later studies [5,6] however argued against these results, which made the measurements of the angular anisotropy carried out in the present work to be of particular interest.

A great body of experimental data was recently obtained on subbarrier fusion cross sections, however, in all these investigations fusion-fission and fusion-evaporation cross sections have been obtained within a wide high-energy range, while in the subbarrier region there are only several points, where the energy is below the barrier by 1–8 MeV. In addition, some works have been published recently, in which the cross section of the evaporation reactions differs by one order of magnitude, see [6] and references in it. Our interest in the study of such deep subbarrier interaction is connected not only with a possibility of investigating the fusion cross section and discussing the mechanism of subbarrier reaction enhancement in the case of the spherical nuclei interaction, but also with a possibility of investigating the structural effects in different fission modes of compound nuclei produced in reactions with heavy ions. Earlier this type of investigations has been carried out only using reactions with light charged particles [7]. And finally, the study of deep subbarrier reactions using Pb and Bi nuclei is of special interest, since on the one hand they make a basis for the synthesis of superheavy elements in cold fusion reactions, and on the other hand, are daughter nuclei in the case of cluster decay of nuclei from Ra to U. The employed methods allow one to investigate deep subbarrier reactions with the cross section level of up to 10^{-36}, which opens up new perspectives for analysis of the possibility of new elements synthesis as well as for the study of inverse reactions of cluster decay.

Experimental Procedure and Results

Beams of ^{16}O obtained at the tandem accelerator (NFIN, Catania, Italy) were focused onto a ^{208}Pb target located in the center of a scattering chamber. A target of 270 $\mu g/cm^2$ of ^{208}Pb (99.1 % enrichment) was evaporated onto a ~ 30 $\mu g/cm^2$ carbon backing. The target was oriented with a carbon side facing the beam. The energies and fluences of the accelerated ^{16}O beams, used for this experiment, the loss energy interval for passing through the target of ^{16}O beam, the obtained cross sections and the angular anisotropy of the fission fragments of $^{224}Th^*$ compound nuclei are presented in Table 1.

Table 1. Experimental conditions and results

Energy, MeV	Loss energy interval of ^{16}O for target, MeV	Fluence of ^{16}O, ions/cm^2	Cross-section of ^{224}Th fission, mb	Fission fragments anisotropy
78	77.8 – 77.0	$1.4 \cdot 10^{14}$	4.3 ± 0.1	1.20 ± 0.10
75	74.8 – 74.2	$1.35 \cdot 10^{15}$	$(6.2 \pm 0.1) \cdot 10^{-2}$	1.26 ± 0.15
73	72.8 – 72.4	$4.1 \cdot 10^{15}$	$(2.3 \pm 0.1) \cdot 10^{-3}$	1.23 ± 0.15
68	67.8 – 67.2	$5.6 \cdot 10^{15}$	$(3 \pm 2) \cdot 10^{-6}$	—

Single fission fragments were detected in the backward angular ranges of 90° – 164° and 198° – 270° by using mica dielectric detectors with an area of 170 cm^2. The details of this method were discussed earlier in work [8]. The background of the fissile element contamination in the target, backing and mica detectors was less than 1 event for the whole detector area.

The experimental values of the angular anisotropy of fission fragments presented in Table 1 were derived by extrapolation of the experimental angular distributions $W(\Theta)$ (see Fig. 1) to the angles $\Theta = 90°$ and $\Theta = 180°$, using an ordinary expression $W(\Theta) = a + b\cos^2\Theta$. The error of the value of the angular anisotropy is no more than 10%, the statistical and fitting error included. The experimental fission fragment anisotropies are shown in Fig.2, as a function of $E_{c.m}$. The solid marks present our experimental data, the open marks are from previous works [5, 9-11]. One can see that in the investigated energy range in our experiment there is a plateu characterized by the relation $W(180°)/W(90°) = 1.2$ in the angular anisotropy.

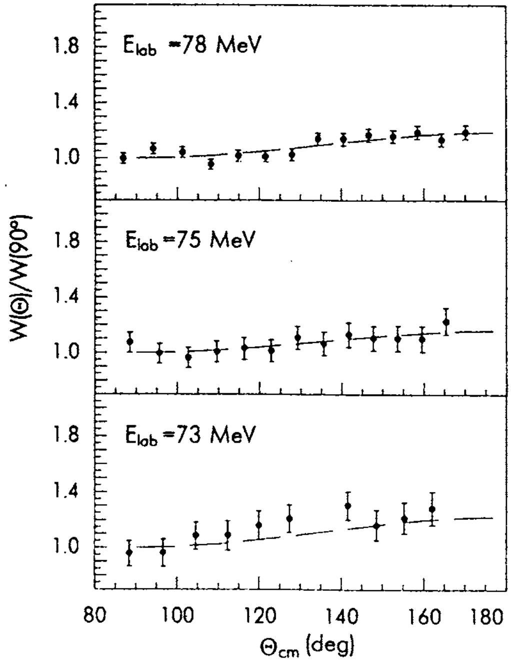

Fig.1. The experimental fission fragment angular distributions as a function of the center-of-mass scattering angle. The error bars on the data points indicate statistical uncertainties

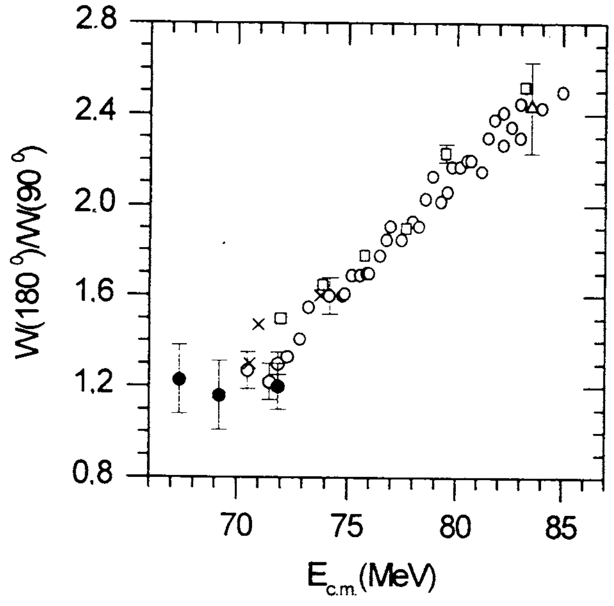

Fig.2. The experimental (present work) anisotropy of fission fragments (solid points) as a function of $E_{c.m.}$. The open points are results of previous measurements (o — Morton et al. [5]; □ — Vulgaris et al. [9]; Δ — Back et al. [10]; x — Marakami et al. [11])

Analysis

The estimation of the fission and evaporation cross section necessarily involves both the details of the compound nucleus formation process and relative competition between fission and other modes in the ^{224}Th compound nucleus decay process.

The fusion/fission cross sections and production cross sections of the final nuclei in evaporation channels in works [8,12] were analysed in detail. Therefore, this work only makes an outline of the basic results provided by these investigations, whereas the main attention is paid to the angular distributions of fission fragments.

A. Cross Sections. Calculations of the fusion cross sections were tested: a) within the Wong approximation; b) within the standard approximation of an inverted parabola with the nuclear potential in the form of Igo; c) by the introduction of the vibrational zero-point motion of the surface; d) by the method of coupled channels using a standard software package CCFUS. Figure 3 presents our experimental fission cross sections, data from different works unified in Ref.5 and results of calculations with the use of the coupled-channels approach. It is evident that at an ion energy of $^{16}O \leq 80$ MeV the subbarrier fusion cross sections, calculated using the Wong approximation or using the CCFUS software package disregarding the channel coupling, are going down much sharper and at an energy of $E_{lab} = 72.5$ MeV are by nearly an order of magnitude lower than the experimental value of the fusion cross section, whereas taking into account of the channel coupling or zero-point vibrations leads to the increase in the cross section.

To analyse the fission and evaporation cross sections, we used a statistical model of the deexcitation process of compound nuclei which, for the sake of universality, uses the minimum number of physical assumptions and parameters [13]. It is shown that the evaporation reaction cross sections are well described within the statistical model framework taking into account shell effects according to Ignatyuk and it is also shown that such calculations, making use of only one set of model parameters, namely, the scaling

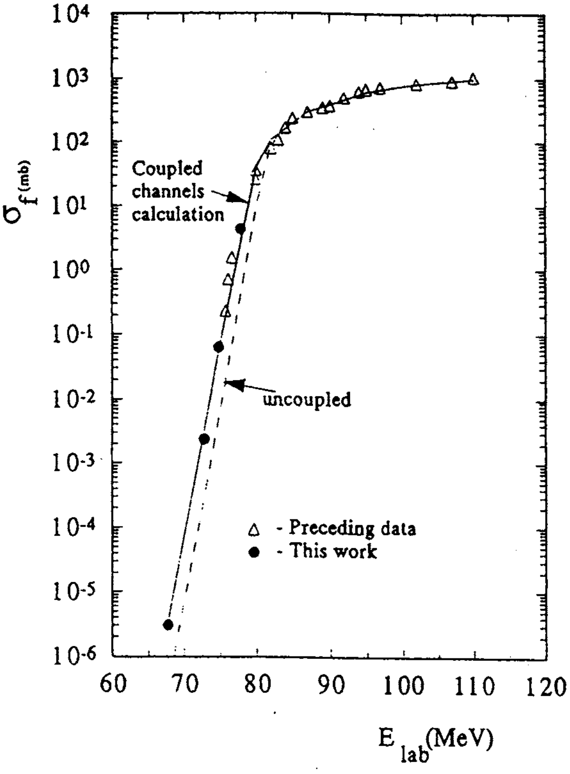

Fig.3. The experimental fission cross section and results of calculations in coupled channel approach

factor to the liquid-drop barrier of Cohen, Plasil and Swiatecki $C = 0.65 + 0.7$ and the ratio of the level density parameters $\hat{a}_f/\hat{a}_v = 1.0$, correctly describe the cross sections of evaporation reactions in a wide range of compound nuclei up to superheavy elements and $C = 0.7$; $B_f(l = 0) = 5.9$ MeV, respecively. Figure 3 presents the comparison of the experimental data of the σ_{xn}, $\sigma_{ev} = \sigma_{xn} + \sigma_{pxn} + \sigma_{\alpha xn}$ and $\sigma_{ev} + \sigma_f$ cross sections with the results of calculations. The energy scale is presented as a difference between the excitation energy and the Bass-barrier excitation energy $E^* - E^*$ (Bass). One can see from Fig.4 that in spite of a wide range of cross section variations, the calculations reproduce well enough both the relative and absolute values of the cross sections. In the interval of excitation energies of 20-30 MeV, the contributions of the two fission chances to the total cross section are approximately equal, which has to be taken into account in the analysis of different characteristics of the fission process. Note that our experimental values of the evaporation cross sections differ by an order of magnitude from the data obtained in [5], but agree with the results of earlier work [9].

B. Angular Distrbutions. The angular distributions of fission fragments were found by calculating the relative probability of the fragments emitted at a specified angle as a function of the angular momentum of the nucleus, with the use of the statistical transition state model (TSM). With consideration for the possibility of nucleons and light particles being evaporated, which precedes the fission, the angular distributions of fission fragments may be written as

$$W(\theta) \approx \sum_{l=0}^{l_p} (2l+1) \sum_{i=0}^{m} \sigma_f(l_i, N_i, Z_i) I_0\left(\frac{l_i^2 \sin^2\theta}{4K_{0i}^2}\right) \exp\left(-\frac{l_i^2 \sin^2\theta}{4K_{0i}^2}\right),$$

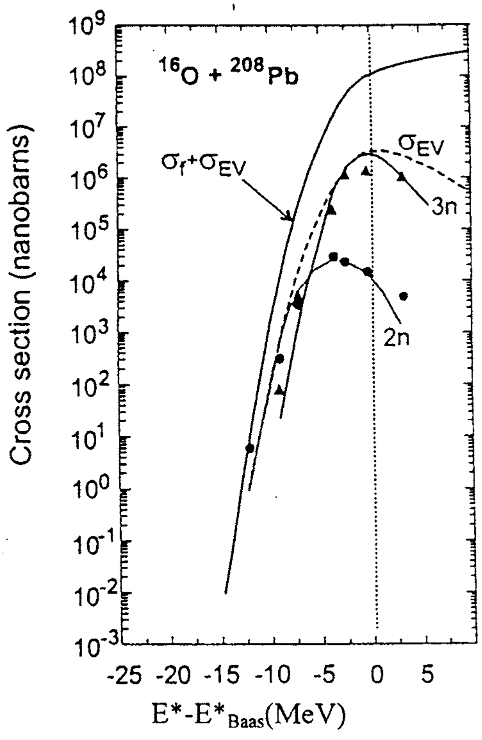

Fig.4. The experimental data cross sections (points) σ_{xn}, $\sigma_{ev}=\sigma_{xn}+\sigma_{pxn}+\sigma_{\alpha xn}$ and $\sigma_{ev}+\sigma_f$ and the results of calculations (solid line)

where l_p is the maximum angular momentum: Z_j and N_i are the numbers of the protons and the neutrons, respectively, in the corresponding daughter nucleus; l_i is the angular momentum of the daughter nucleus, which decreases by 1 or 4 depending on what is emitted: a neutron, a proton or an α particle. The total fission cross section of the initial nucleus is assumed to be as follows

$$\sigma_f = \sum_{l=0}^{l_p} \sigma_l \sum_{i=0}^{m} \frac{\Gamma^l_{fi}}{\Gamma^l_{fi} + \sum\limits_{\nu=n,p,\alpha} \Gamma^l_{\nu i}} \prod_{k=0}^{i-l} \sum_{\eta=n,p,\alpha} \frac{\Gamma^l_{\eta k}}{\Gamma^l_{fk} + \sum\limits_{\nu=n,p,\alpha} \Gamma^l_{\nu k}} .$$

As is seen the angular distribution of fission fragments is characterized by the value $I^2 \sin^2\Theta/4K_0^2$, where $K_0^2 = J_{\rm eff} * T/h^2$. In terms of the transition state model the effective moment of inertia depends on the value of the angular momentum of a nucleus, and is defined by the saddle configuration of the nucleus: $1/J_{\rm eff} = 1/J_{\|} - 1/J$, where $J_{\|}$ and J are the moments of inertia at the saddle point relative to the parallel and perpendicular symmetry axes of the fissioning nucleus, respectively. Thus, to calculate the angular anisotropy, it is necessary to know: the distribution of the angular momentum, temperature T at the saddle point (for taking account of the chances of the fission) and the effective moment at the saddle point as a function of the fissionability and angular momentum. Most fully all the necessary corrections to $J_{\rm eff}$ are given in [10]. The production and decay of the compound ^{224}Th nucleus is considered near the interaction barrier, which is characterized by $\langle I^2 \rangle \le 500$, all the corrections (spin-dependent saddle point shapes, post-scission reorientation, etc.) are of no more than 10%. Table 2 presents the experimental data and calculated values of σ_f, $W(180°)/W(90°)$ for the first chance of the fission and for the emission fission.

Table 2. Experimental data and calculated values of σ_f, $W(180°)/W(90°)$ for the first chance of the fission and for the emission fission

E^*, MeV	E^*, MeV	σ_f^{exp}, mb	$W^{180°}_{\mathrm{exp.}}/W^{90°}_{\mathrm{exp.}}$	$\sigma^{\mathrm{cal.}}_{f(0)}$, mb	$\sigma^{\mathrm{cal.}}_{f(\mathrm{tot})}$, mb	$W^{180°}_{0}/W^{90°}_{0}$	$W^{180°}_{\mathrm{tot}}/W^{90°}_{\mathrm{tot}}$	$J_{\mathrm{sph}}/J_{\mathrm{eff}}$
72.6	20.8	$(2.3 \pm 0.1) \cdot 10^{-3}$	1.23 ± 0.15	$1.4 \cdot 10^{-3}$	$2.9 \cdot 10^{-3}$	1.21	1.23	0.85
74.6	22.7	$(6.2 \pm 0.1) \cdot 10^{-2}$	1.16 ± 0.15	$1.5 \cdot 10^{-2}$	$5.1 \cdot 10^{-2}$	1.2	1.24	0.85
77.6	25.5	4.3 ± 0.1	1.2 ± 0.1	0.8	2.5	1.23	1.31	0.85

As is seen, the angular anisotropies are well described at $J_0/J_{\mathrm{eff}} = 0.85 \pm 0.05$, and, when brought to the zero angular momentum, the relation J_0/J_{eff} varies only slightly and is equal to 0.9 ± 0.05, which is in reasonably good agreement with the calculations within the framework of the Sirk's model (Rotating Finite-Range Model). The value of the effective moment of inertia J_{eff} is equal to 5100 fm^2 at $r_0 = 1.17$ fm.

Conclusion

There have been measured fission cross sections of ^{224}Th compound nuclei in reaction ^{16}O + ^{208}Pb deep in the subbarrier energy region. In the range of excitation energies of 20–30 MeV the contributions of the two fission chances to the total cross section are approximately equal, which has to be taken into account in the analysis of angular distribution and other characteristics of the fission process. Comparison of the calculated angular anisotropy with the experimental values shows no evidence for anomalously large fission fragment anisotropies at beam energies deep in the subbarrier region. Thus, standard models of fusion and fission are able to describe experimental data, and the results of the TSM model calculations are in agreement with the experimental anisotropies.

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