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CROSS-SECTIONS OF BISMUTH NUCLEI FISSION ON THE SECONDARY BEAM OF ^{6}He

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The cross-sections for fission of ^{209}Bi induced by secondary beams of ^{6}He and ^{4}He are measured in analogous conditions. There is a good agreement with formerly published data on fission cross sections. In the case of the reaction ^{4}He + ^{209}Bi, the cross-section of the fission of ^{209}Bi induced by ^{6}He are significantly higher than the corresponding α-particle-induced fission cross-section. A large energy shift is observed of the threshold for the fission reaction ^{6}He + ^{209}Bi in comparison with the reaction ^{4}He + ^{209}Bi. The analysis of different factors which might be responsible for the observed effect in the fission reaction ^{6}He + ^{209}Bi is also presented.

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

Изучение сечений деления ядер висмута на вторичном пучке ионов ^{6}He

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Измерены в аналогичных условиях сечения деления ^{209}Bi на вторичных пучках ^{6}He и ^{4}He. Получено согласие экспериментальных данных по сечению деления ^{4}He + ^{209}Bi. Измеренные сечения деления ^{209}Bi ионами ^{6}He значительно превышают сечения деления α-частицами. Получено смещение порога деления для реакции по ^{6}He + ^{209}Bi по сравнению с реакцией ^{4}He + ^{209}Bi. Анализируются различные аспекты для объяснения наблюдаемых особенностей при делении ^{209}Bi ионами ^{6}He.

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1. Introduction

The first experiments on the BEVALAC measuring the interaction cross-section at an energy of 800 MeV/A showed [1] that the structure of nuclei far from stability can be studied by using secondary beams of radioactive nuclei. Later on, at the GANIL, RIKEN, JINR and MSU (Michigan) there was carried out a series of experiments studying the interaction cross-sections, the elastic scattering differential cross-sections, the fragmentation and electromagnetic dissociation on radioactive beams with energies from 10 MeV/A up to 100 MeV/A [2—6]. Basing on these data there were extracted values of radioactive nuclei radii and was confirmed the hypothesis of neutron halo existence in nuclei of ^{11}Li. At the same time, it is evident that further efforts are necessary to investigate the interactions of ^{6}He, ^{8}He, ^{11}Be and ^{17}B for which the existence of a neutron halo of one or several neutrons is possible. In particular, the hypothesis of the neutron halo existence in the nuclei of ^{6}He is finding its theoretical and experimental grounds [4,7,8]. This fact can lead to a decrease of the Coulomb barrier for the reaction of fusion with ^{6}He nuclei, which in its turn will lead to a growing probability of compound nucleus fission. The large angular momentum, introduced into the compound nucleus of ^{6}He, as compared with ^{4}He, also leads to the decrease of the fission barrier of the product nucleus. On the other hand, the extended distribution of neutron density in a ^{6}He nucleus may cause its disintegration in the heavy nucleus field of the target which will lead to the decrease in the cross section of complete fusion of interacting nuclei and, thus, to a smaller fission probability. From this viewpoint, it is of interest to study the fission or fusion cross section with such an exotic nucleus as ^{6}He.

The present research is an attempt to obtain data on the fission cross sections of astatine-213 and astatine-215 nuclei at the irradiation of bismuth-209 nuclei with a secondary beam of ^{6}He and ^{4}He ions under comparable conditions.

2. Experimental Method

Figure 1 presents a scheme of our experimental facility for the production of secondary beams of ^{6}He and ^{4}He and for the investigation of ^{213}At and ^{215}At nuclei fission by these nuclei.

The primary beam of ^{11}B ions accelerated on the U400 was focussed onto a specially manufactured cooled rotating tantalum target designed to absorb completely ^{11}B ions of an energy of 200 MeV. Separation of the Ta + ^{11}B reaction products and their formation into secondary beams were performed by means of an optical-ion system described elsewhere [9]. To improve the purification of the ^{6}He secondary beam of other particles, an Al degrader, with a thickness of up to 100 μm, was installed between the dipole magnets MT1 and MT2. This brought about a change of particles magnetic rigidity. In this connection, the magnetic rigidity in the second dipole MT2

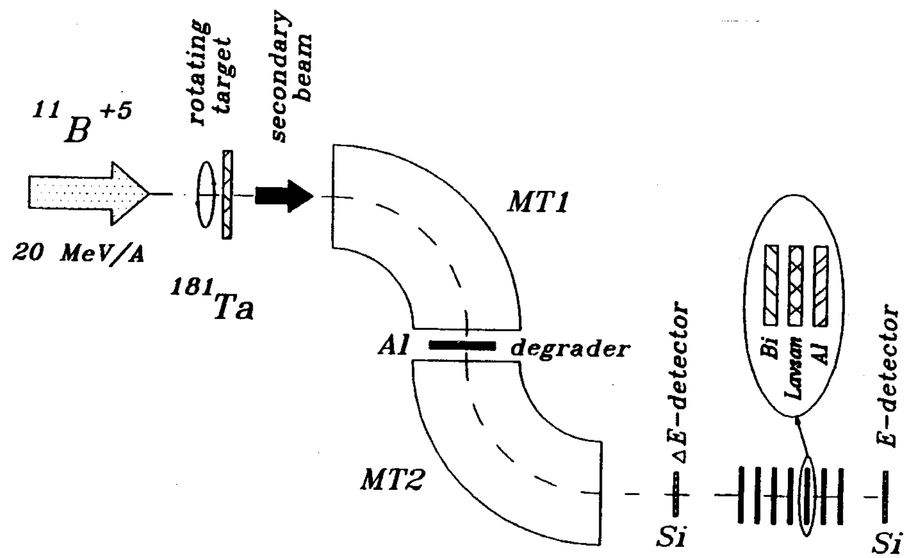

Fig. 1. The experimental set-up scheme for the production of secondary beams

was chosen to provide a better ^{6}He or ^{4}He beam purification from other particles. The shaping of the secondary beam, the control of its quality as well as particle monitoring were performed by means of a system of telescopes of $\Delta E \times E$-detectors including surface-barrier detectors of the ΔE-type with thicknesses ranging from 50 to 70 μm and of the E-type with thicknesses reaching 2.5 mm.

Figure 2 shows a typical spectrum of a shaped secondary beam of ^{6}He used in experiments on ^{215}At nuclei fission. The intensity of ^{6}He with an energy of 50 MeV and a resolution of ≅ 3% reached 200 pps at a ^{6}He purity of ≅ 95%. For the case of a ^{4}He beam used as a secondary beam, the intensity of ^{4}He was limited to several thousands pps, the beam purity at a ^{4}He energy of 54 MeV reached 98%, (the energy resolution ≅ 3%). Because of a low intensity of secondary beam particles, a high-efficiency method of registering compound nuclei fission had to be used. For the purpose, special «sandwich-type» arrays (fig.1.) with consecutively alternating targets of ^{209}Bi, polymer plates for registration of fission fragments and additional absorbers made of aluminium were manufactured. Such arrays were installed perpendicularly to the incident beam of secondary particles. The targets were manufactured from bismuth-209 by

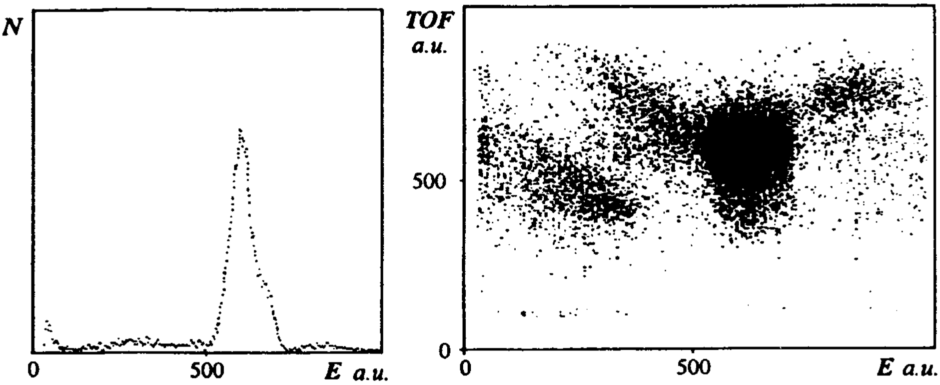

Fig.2. Spectra of shaped secondary beam of ^{6}He used in experiments on fission of ^{213}At and ^{215}At

the method of vacuum sputtering of metallic bismuth onto a 7 μm-thick aluminium backing. Aluminium foils and bismuth targets were tested for uranium contamination by using the neutron-activation method. The analysis showed that the content of uranium in bismuth targets and aluminium backings did not exceed a value of 10^{-7} at/at.

For registration of fission fragments polyterephthalate films ≅ 55 μm-thick were chosen. In this case the effective layer of bismuth R_{eff} (mg/cm^2) was determined with the account of the absorption of a part of fragments it brought along [10]. After a 30—48 hours irradiation of an array with a beam of secondary particles the bismuth and aluminium layers were removed and the polyterephthalate was subjected to chemical treatment in NaOH solutions for visual identification of fission fragments. The diameter of fission fragments was increased to 8—10 μm and the search and counting of tracks was performed using a microscope of 100-200 magnification.

We performed also background experiments on fission of Bi targets by a scattered neutron flux. The observed effect of ^{213}At and ^{215}At nuclei fission by nuclei of ^{6}He and ^{4}He could not be explained by fission of uranium admixtures in Bi or by fission of ^{209}Bi nuclei by scattered neutrons.

3. Experimental Results and Discussion

In Figure 3 one can see the observed by us dependencies of fission cross section changes from the energy of bombarding particles (in the center of mass system) ^{6}He and ^{4}He. One can also find there open squares denoting

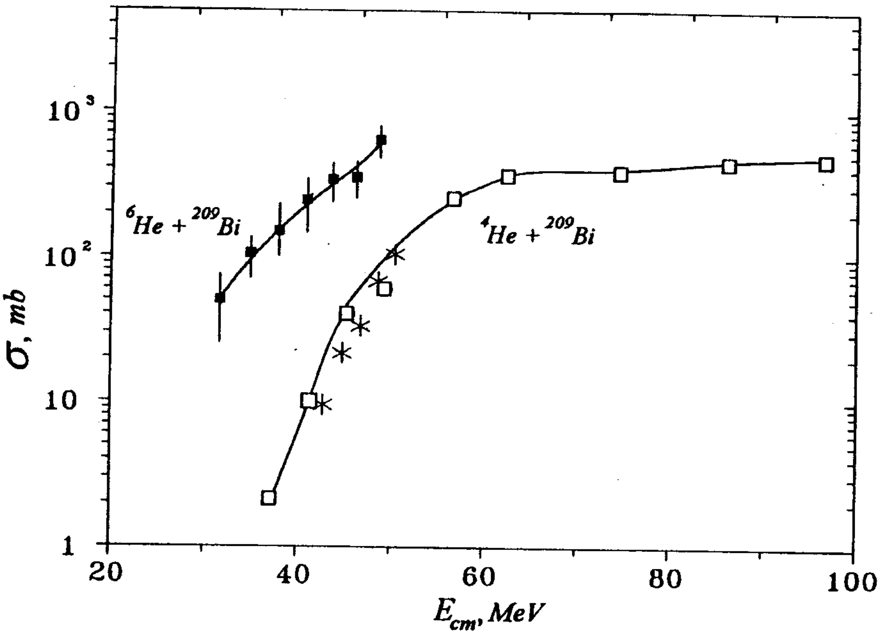

Fig.3. The dependencies of the fission cross sections on the energies of bombarding particles of ^{6}He and ^{4}He (in the c.m.s)

the experimental cross section values of ^{213}At fission by α-particles cited from refs. [11,12].

From the comparison of these data it is well seen that in the case of ^{213}At fission by α-particles (stars) there is a good agreement with the earlier measured values, which is an indication to the correctness of cross section measurements via such a method.

In this connection it is of interest to consider the growth of ^{209}Bi cross section of fission by nuclei ^{6}He as compared with the fission by ^{4}He nuclei. It is evident from the figure that the deviation of the curve for cross sections of nuclei fission by α-particles is substantially greater than the statistical errors.

Of substantial interest is a large energy shift ≅ 15 MeV between the thresholds of the reactions ^{4}He + ^{209}Bi and ^{6}He + ^{209}Bi. One can point out at least three reason causing the energy shift in these reactions:

- difference in the Coulomb fusion barriers;
- difference in the fission properties of the produced compound nuclei of ^{213}At and ^{215}At;
- difference in the angular momenta introduced into the compound nucleus at the same incident ion energy in the c.m.s.

3.1. Difference in the Coulomb Barriers of Fusion

As it follows from ref. [13], in the sub-barrier region and near the fusion barrier a considerable growth of fusion cross section is expected for the case of an interaction with neutron-rich nuclei. Here the repulsion potential covers greater distances than in stable nuclei and, as a consequence, the Coulomb barrier between the nuclei with a halo can be lower than between stable partners. The excitation of a soft giant mode at this interaction also assists fusion [4]. Calculations of such effects are very labour-consuming and for the time being we are not able to give quantitative estimation.

There were considered several standard parameterizations for the nuclear part of the ion-ion potential which were suggested in different papers. All of them give close values for the nuclei considered and for our numerical calculations we have used the potential suggested in ref. [22]. For the Coulomb barrier in these reactions there was obtained $V_b = 20.6$ MeV for the reaction ^{4}He + ^{209}Bi and $V_b = 20$ MeV for the reaction ^{6}He + ^{209}Bi. It can be seen that the difference in the Coulomb barriers is too small to explain the energy shift.

Experimental data on the cross sections of fission were obtained at the energies substantially greater than the Coulomb barrier that is why in this energy region one can disregard the coupled-channel effects.

3.2. Account of Compound Nuclei Properties

The full fusion cross section of two spinless nuclei in terms of partial waves can be written down as follows:

$$\sigma_{fus}(E) = \sum_{l=0}^{\infty} \sigma_l(E) = \frac{\pi}{k^2} \sum_{l=0}^{\infty} (2l + 1) T_l(E). \qquad (1)$$

In reactions of two nuclei complete fusion, partial penetrations σ_l determine the spin population of a compound nucleus and the competition between particle evaporation channels and fission channels.

For nuclei with the initial spins S_1 and S_2 formula (1) will be rewritten in the following way:

$$\sigma_{fus}(E) = \sum_{J}^{\infty} \sigma_J(E) = \frac{\pi}{k^2(2S_1 + 1)(2S_2 + 1)} \sum_{l,J} (2J + 1) T_l(E) \qquad (2)$$

and the summing up over J is performed in the interval $|S-l| \leq J \leq |S+l|$ and $S = S_1 + S_2$.

The analysis of the data was performed in the frame of the statistical approach to the description of the compound nucleus decay. In this approximation the total fission cross sections [14] within this approach are described by the expression:

$$\sigma_{fiss} = \frac{\pi}{k^2} \sum_{l=0}^{l_{cr}} (2l + 1) \frac{\Gamma_f(l)}{\Gamma_f(l) + \sum_{\nu} \Gamma_\nu(l)}, \quad (3)$$

where l_{cr} is the maximum angular momentum above which the probability of the compound nucleus formation is negligibly small; Γ_f, fission width defined, in the main, by the fission barrier B_f and the value of the parameter of level density in the fission channel a_f, Γ_ν are evaporation widths dependent on the binding energy of the ν particle and on the corresponding parameter of level density a_ν. In this approach the main parameters for the description of $\sigma_f(E)$ are the value l_{cr}, the height of the fission barrier B_f and the ratio of density levels a_f / a_ν.

For the calculation of the values Γ_f and Γ_ν there was used the approach of ref. [15] suggesting and grounding a semiphenomenological method of accounting the influence of shell, super fluid and collective effects on the energy dependencies of level densities. At setting the parameters a_f and a_ν there were used the results of ref. [16] where through the analysis of the fission probability of nuclei with $Z = 81$—83 by light particles there had been obtained a value $a_f / a_\nu = 1.03 \pm 0.01$. The B_f of these nuclei were measured experimentally. There are no experimental data on the value of l_{cr} for the interaction of ^{6}He with heavy nuclei that is why there have been used the l_{cr} values calculated by the model [17]. The model has been selected on the assumption that for ^{4}He ions it gives values of σ_{fus} and l_{cr} which are in satisfactory agreement with the values obtained in ref. [16]. In the calculations of the integral cross sections the contribution of the post-emission fission is taken into account by means of the method presented in ref. [16].

The results of our analysis are demonstrated in fig.3 where a solid line shows the dependence $\sigma_f(E)$ calculated for ^{215}At with $B_f = 15.3$ MeV. The barrier value we have obtained is in good agreement with the value $B_f = 15.5$ MeV obtained in the model of Myers and Swiatecki [18]. Other approaches to the description of B_f [19,20] in the region of nuclei with $Z \cong 84$ produce results which are in agreement with [18], that is why it seems impossible to choose the most adequate model in this case.

It should be noted, that for the reaction studied $^6He + ^{209}Bi$ the results of calculating $\sigma_f(E)$ depend strongly on the choice of parameters B_f and a_f / a_v. That is why, even with the possible ambiguities in setting these data taken into account, the results of this analysis cannot serve as good enough grounds for the application of model [17] to the description of the input channel in reactions with ^6He.

3.3. Influence of Introduced Angular Momenta

In this subsection we are using, for a more spectacular representation of data, a different approach suggested in ref. [23] for separation of evaporation channels and compound nucleus fission. The cross section for evaporation of particles is written as follows:

$$\sigma_{evap}(E) = \sum_J \sigma_J(E) W(E^*, J), \tag{4}$$

where $W(E^*, J)$ is the survival probability for a nucleus in the evaporation cascade with passing by the fission channel.

For nuclei in the region $30 < Z^2/A < 35$ it has been found [23] that there exists for this value a sharp cut by the angular momentum

$$W(E^*, J) = \begin{cases} 1 & J < J_{evap} \\ 0 & J > J_{evap} \end{cases} \tag{5}$$

with the J_{evap} values independent of the input channel and the excitation energy of the compound nucleus. They are just linear functions of the parameter Z^2/A.

In this approximation the evaporation and fission cross sections can be written down in the following way:

$$\sigma_{evap}(E) = \frac{\pi}{k^2} (J_{evap} + 1)^2 \tag{6}$$

$$\sigma_{fiss}(E) = \pi R_b^2 (1 - V_b/E) - \frac{\pi}{k^2} (J_{evap} + 1)^2. \tag{7}$$

In the given expression for the sake of simplicity there has been used a classical expression for the fusion cross section in the near-barrier region, but in calculations we use a quasi-classical variant [24] of the single channel model of the critical distance [21]. At high energies of incident particle, where the contribution into the fusion cross section is made by many partial waves, the Coulomb barrier parameters in expression (7) are to be substituted by the parameters determining the potential at a distance $R_{cr} = A_1^{1/3} + A_2^{1/3}$ [21].

Thus, a strong dependence on the incident ion orbital angular momentum is contained both in the input and output channels. By parameterization of the potential from ref. [22] we have obtained for both the reactions the value of the potential at a critical distance $\cong -7$ MeV. The negative sign of the potential shows that at high energies of incident ions the fusion's full cross sections diminish with energy increase.

Having rewritten the fission cross section as:

$$\sigma_{fiss}(E) = \pi R_b^2 (1 - V_{eff}/E) \tag{8}$$

one can see that the fission cross section is well described by a known classical expression for the reaction cross section possessing though an «effective potential»:

$$V_{eff} = V_b + \frac{(J_{evap} + 1)^2 h^2}{2\mu R_b^2}. \tag{9}$$

Based on this one can find the expression for the energy shift between the fusion cross section and the cross section of compound nucleus fission:

$$\Delta E = \frac{(J_{evap} + 1)^2 h^2}{2\mu R_b^2}. \tag{10}$$

This formula points at a strong dependence of the energy shift on the reduced mass of the system, which in our case is 1.5 times greater for the reaction with ^{6}He than for the reaction with ^{4}He.

In the sharp cut approximation (5) one obtains a very steep slope in the fission cross sections at low energies that is why we have introduced an additional parameter ΔJ into the function W:

$$W(E^*, J) = \left[1 + \exp\left(\frac{J - J_{evap}}{\Delta J}\right)\right]^{-1}. \tag{11}$$

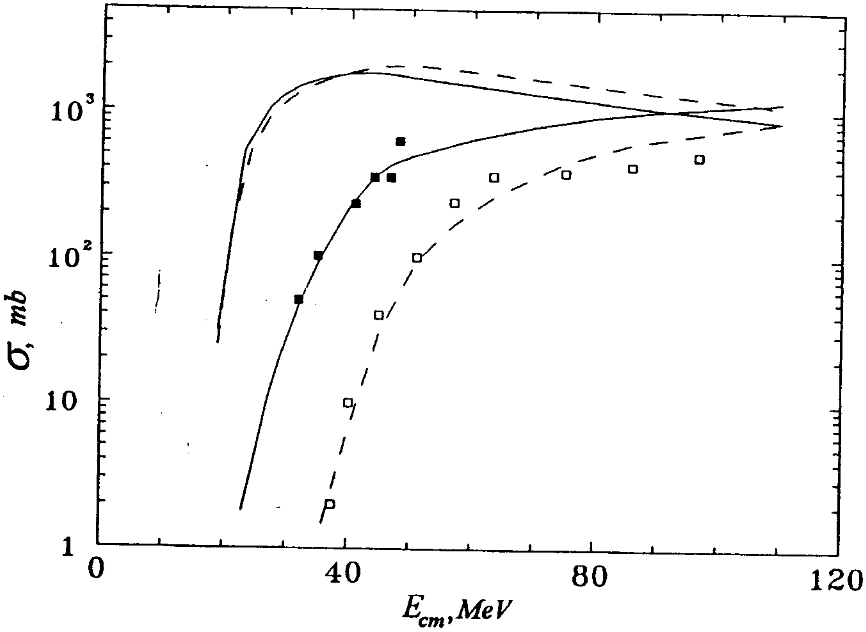

Fig.4. The result of calculating the dependence of fission and evaporation cross sections on the energy of bombarding particles (in the c.m.s.) ^6He (solid lines) and ^4He (dashed lines)

Parameters J_{evap} and ΔJ can be determined from the statistical theory of compound nucleus decay. In the given work we have calculated them as free parameters which were selected for better description of the data.

The results of calculating the evaporation and fission cross sections are presented in fig.4. The obtained parameters: $J_{evap} = 26.2$ and $\Delta J = 1.9$ for the reaction with ^6He and $J_{evap} = 26.2$ and $\Delta J = 0.9$ for the reaction with ^4He agree with the systematics [23] which gives for two reactions the J_{evap} values of $32h$ and $29h$, correspondingly.

We see that the threshold values of angular momenta at which there opens a fission channel are practically identical for both the reactions. Thus, the energy shift between the fission cross sections can be explained by different reduced masses in the input channels of these two reactions. To illustrate this statement we have presented in fig.5 the calculated partial cross sections of evaporation and fission in two reactions at an energy of 40 MeV in the center of mass system. One can see that in the reaction $^6He + ^{209}Bi$ a large angular momentum is introduced into the compound nucleus and the fission channel turns out to be open.

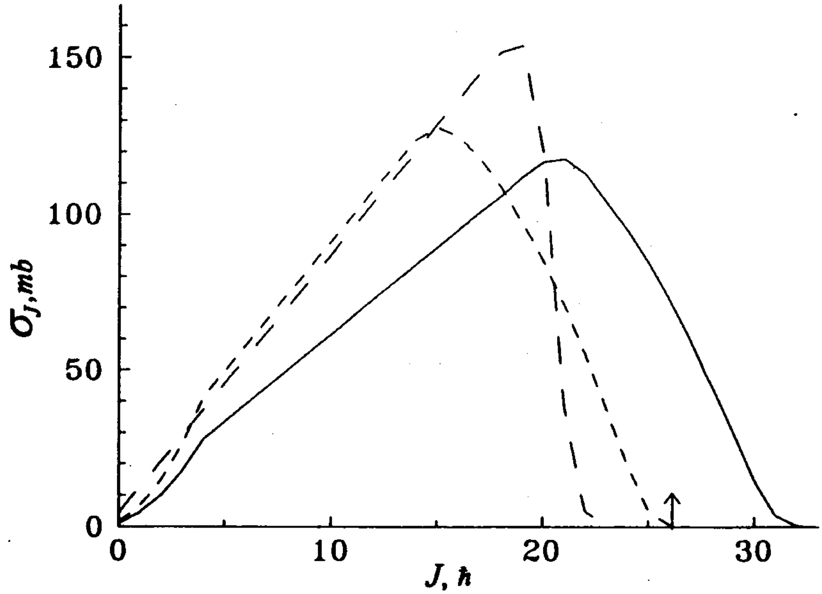

Fig.5. The calculated partial cross sections of fusion for the reaction ^4He + ^{209}Bi (short dashed lines) and ^6He + ^{209}Bi (solid lines) at an energy of 40 MeV (in the c.m.s.). The arrow points out the value of J_{evap}. Long dashed line denotes the calculation for ^4He disregarding the spin of ^{209}Bi nucleus

In the same figure one can find a calculation disregarding the spin of ^{209}Bi nucleus. It is evident that a large spin $9/2\hbar$ leads to the erosion of the upper limit of partial penetrations for fusion. In this case the dependence of the calculation results on parameters J and ΔJ appears to be very weak. Thus, the reaction of fusion with even-even nuclei are preferable for studying the competition of evaporation and fission.

Based on the factors considered above and on the experimental data available it is difficult to give preferences to either of them. The picture can be clarified through the comparison of the fission cross sections and of fission fragments angular distributions for two or three different input channels, leading to the same compound nucleus (for example in the reactions ^6He + ^{206}Pb and ^4He + ^{208}Pb or ^6He + ^{187}Os, ^4He + ^{189}Os and ^{187}Re + ^6Li). In this case $\sigma_{fiss}(E)$ and $W(\Theta)$ will mainly depend on the difference in the l_{cr} of the compared reactions or by the structure of the nucleus ^6He.

It is evident, also, that investigations on secondary beams open new possibilities for studying the fission of such compound nuclei, which are impossible to obtain in reactions with heavy ions at acceleration of stable isotopes.

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