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Fusion-fission reactions induced by ^{6}He-ions

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Abstract. The experimentally measured excitation functions for the fission and 4n evaporation channels are presented for the ^{6}He + ^{209}Bi reaction. The secondary ^{6}He beam was produced using the special beam line (Q4DQ-spectrometer) of the U400M accelerator at FLNR, JINR. The comparison of the obtained experimental data with similar results for the ^{4}He + ^{209}Bi reaction shows that in the case of the ^{6}He + ^{209}Bi reaction a significant enhancement of the cross-section is observed for energies above the barrier. In order to get an agreement between the experimental data and the theoretical calculations it is necessary to reduce the Coulomb barrier by 15–20% , which corresponds to an increase of the parameter r_0 of the nuclear potential up to 1.5–1.6 fm.

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1 Introduction

In the past few years, in different scientific centers, intensive experimental studies have been performed using secondary beams formed from the radioactive products of nuclear reactions. Lately there has been a growing trend to use secondary beams as a means of investigating the interaction cross-sections of these exotic nuclei with the target nuclei. These data help to obtain information on the structure of nuclei far from the line of stability, on the distribution of nuclear matter and on charge radii. In particular, experimental evidence was found for the existence of the neutron halo (^{11}Li) and skin (^{6}He) in the neutron-rich nuclei [1,2]. The mechanism of reactions induced by these nuclei has specific features due to the weakly bound valence neutrons. Most interesting from this point of view is the fusion channel. This served as a pushing factor for many studies, dedicated to the sub-barrier enhancement of the complete-fusion cross-section in reactions induced by neutron-rich nuclei such as ^{6}He and ^{8}He. However, it is evident that measurements of the fusion cross-section are of interest in the region of the Coulomb barrier as well, because in this case the weakly bound neutrons in ^{6}He, ^{8}He and others of this type should influence the process. This interest follows also from the fact that the mechanism of such an influence in the region above the barrier may be different from those, which play an important role at energies lower than the Coulomb barrier. The situation above the barrier is much more complex. It hampers the observation of the contribution from other channels to the fusion process. In this connection it is important to correctly choose the decay channel of the compound nucleus, which indicates that the complete fusion of the interacting nuclei has taken place.

Calculations have been carried out for the reactions ^{11}Li + ^{208}Pb and ^{11}Li + ^{238}U [3–5]. In these papers special attention was paid to the influence on the fusion cross-section of the break-up of ^{11}Li into ^{9}Li and two neutrons in the field of the target nucleus. It was shown that break-up strongly influences the fusion cross-section at energies close to the Coulomb barrier and actually decreases the fusion cross-section. The fusion-fission reaction induced by secondary beams was first performed using ^{6}He beams [6, 7]. However, later experiments [8–14] did not allow making unambiguous conclusions on the influence of the neutron excess on the enhancement of the fusion cross-section (see table 1).

For these experiments, the choice of the target-nucleus is of great importance. If it were too light, the fission cross-section would be small and the low intensity of the ^{6}He beam would make the performance of such experiments very difficult. The target should not be very heavy either (uranium or heavier). The reason is that for heavy nuclei fission is the main decay mode for all values of ℓ and it is difficult to distinguish the influence of other reaction channels on the probability of compound-nucleus formation. Most suitable targets are nuclei close to lead, and in particular ^{209}Bi for which there also exists a detailed

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Table 1. Fusion, fission reactions with neutron halo nuclei.

Year	Reaction	Enhancement of sub-barrier fusion	Ref.
1992	^{238}U(^{11}Li,fusion) theor. prediction	Yes	[5]
1993	^{209}Bi(^{6}He, f)	Yes	[6]
1994	^{209}Bi(^{6}He, 4n)	Yes	[14]
1995	^{209}Bi(^{6}He, f)	Yes	[7]
1996	^{209}Bi(^{11}Be, 4n, 5n) ^{209}Bi(^{11}Be, 3n, 4n)	No	[11]
1997	^{181}Ta(^{32}S, f) ^{181}Ta(^{38}S, f)	Yes	[12]
1998	^{209}Bi(^{6}He, 3n, 4n)	Yes	[8]
	^{209}Bi(^{6}He, f)	No	[9]
	^{209}Bi(^{6}He, 4n)	No	[8]
	^{209}Bi(^{11}Be, xn)	contradiction with theory	[13]
2000	^{238}U(^{4,6}He, f)	Yes	[10]

measurement of the excitation function of the (α, f) reaction [15]. This is of importance in the analysis of the experimental data.

An open question still remains —what is the influence of the structure of the colliding nuclei on the fusion cross-section at energies above the barrier. We address this issue in the present paper.

2 Experiment

The secondary ^{6}He beam was produced in the reaction ^{7}Li(35MeV/A) + Be. The primary ^{7}Li beam from the U400M accelerator was focused on a cooled Be target 3 mm thick. The separation of the products produced in the target from the projectiles and the formation of the secondary beam was achieved with the help of the ion-optical system of U400M (Q4DQ-spectrometer [16]).

The use of four-dipole and quadrupole magnets made it possible to obtain $5 \cdot 10^{4}$ pps of the ^{6}He beam. Better purification of the beam was obtained with the help of a degrader (2 mm of polypropylene) and slits located between the dipoles. The magnetic rigidity was chosen so as to achieve the best possible purification and the necessary beam energy. The spot size on the secondary target and the quality of the beam were controlled by position-sensitive parallel-plate avalanche counters and silicon detectors. The ^{6}He beam did not change its characteristics during a long period of measurement. It was possible to reach up to 98% purity of the secondary beam at the used energy. The energy dispersion of the secondary beam amounted to ±0.6 MeV.

The ^{6}He beam fell on secondary Bi targets (about 700 μg/cm^{2} thick). The targets were prepared by evaporation onto polymer layers 2.5 μm thick. The fission fragments were registered on-line with the help of semiconductor surface-barrier silicon detectors around the targets. The overall geometrical efficiency was 30% of 4π. At the lower energies of the beam (< 60 MeV) the excitation function was measured using plastic track detectors [6,7].

3 Experimental results and analysis

Figure 1 presents the experimentally measured fission cross-section for the reaction ^{6}He + ^{209}Bi as a function of energy. For comparison the data on the ^{209}Bi α-particle-induced fission are shown as well. A difference is observed in the fission cross-sections for the two reactions ^{4}He + ^{209}Bi and ^{6}He + ^{209}Bi. In order to obtain qualitative and, particularly, quantitative information it is necessary to perform comparative analysis of the results on the two reactions.

But before we do this, we have to answer the question whether all fission events in the ^{6}He + ^{209}Bi reaction are the result of the complete fusion of these two nuclei.

Fission in this reaction, besides the complete fusion, may, in principle, arise due to the break-up of ^{6}He into 2 neutrons and an α-particle with the consequent capture either of the neutrons or the α-particle. In the first case, the nucleus ^{211}Bi is formed. At the maximum energy used in our experiment (about 70 MeV), the excitation energy of ^{211}Bi is 33 MeV (23.4 MeV is the kinetic energy of the neutrons and 9.7 MeV is the reaction Q-value). Then only 0.0001 out of all formed compound nuclei can undergo fis-

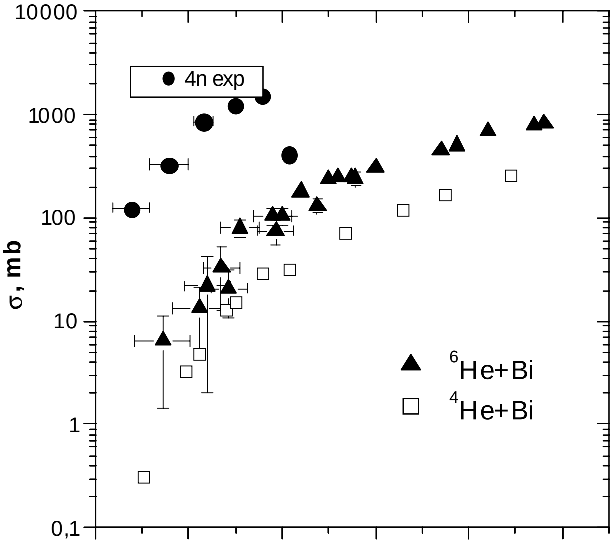

Fig. 1. Fission excitation function for the reaction ^{6}He + ^{209}Bi (black triangles); the solid circles denote the excitation function of the ^{209}Bi(^{6}He, 4n) reaction, the open squares, the data on the ^{209}Bi α-particle induced fission (present work and ref. [7]). The latter are in agreement with [15]. The relations between the excitation energy and the CM energy are given by the following relations: $E^{*} = E_{\mathrm{cm}} + 0.59$ MeV for ^{6}He + Bi reaction and $E^{*} = E_{\mathrm{cm}} - 9.25$ MeV for the ^{4}He particle.

sion, and this is a negligible amount. When the α-particle is captured (also at the maximum energy of ^{6}He) the compound nucleus formed is ^{213}At with an excitation energy ≈ 37 MeV (24 MeV are taken away by the neutrons and the binding energy of the α-particle in ^{213}At is -9.3 MeV). In this case 2% of the compound nuclei ^{213}At may undergo fission and the cross-section for such a process is expected to be less than 5% of the measured fission cross-section, which is equal to 0.8 barn. At lower energies of the ^{6}He beam this value is expected to be even less. Therefore, it can be asserted that all registered fission events in the bombardment of ^{209}Bi with ^{6}He are due to the complete fusion of the interacting nuclei.

In the analysis of the experimental data we used the well-approved programme ALICE-MP [17], which is a modified version of the well-known programme ALICE. The calculation of the fission widths in this programme is based on the classical formula of Bohr-Wheeler, the calculation of the evaporation widths on the formalism of Weisskopf-Ewing. In the calculation of the level densities the relations of the Fermi-gas model are used phenomenologically taking into account the effect of nuclear shells on the level density parameter [18]

$$a_\nu(E^*) = \tilde{a}_\nu\{1 + [1 - \exp(-0.054E^*)]\mathit{\Delta} W_\nu(A,Z)/E^*\},$$

where E^* is the excitation energy of the compound nucleus, $\mathit{\Delta} W_\nu$ the shell correction to the mass of the nucleus, formed after the emission of the particle ν (a neutron, a proton or an α-particle).

The level density parameter in the fission channel a_f is regarded as not depending on the excitation energy and proportional to the asymptotic value of the level density parameter in the particle evaporation channel (this is the assumption of the very small value of the shell correction in the saddle point). The fission barriers are calculated by the relation

$$B_\mathrm{f}(l) = cB_\mathrm{f}^\mathrm{LD}(l) + \mathit{\Delta} W_\mathrm{f},$$

where c is a free parameter, defining the contribution from the liquid-drop component in the fission barrier, $B_\mathrm{f}^\mathrm{LD}(l)$ the fission barrier in the model of the rotating liquid drop of Cohen-Plasil-Swiatecki [19], $\mathit{\Delta} W_\mathrm{f}$ the shell component of the fission barrier of the compound nucleus, which is equal to the module of the shell correction to the mass of the ground state of the nucleus.

In calculating the cross-sections for reactions with particle evaporation and of fission cross-sections for excited nuclei we use two different sets of parameters. One set defines the formation of the compound nucleus and is connected with the geometrical size of the nuclear part of the interaction potential (radius parameter r_0) and its shape (the diffuseness of the potential $d$and its depth V). Numerous calculations of compound-nucleus formation cross-sections carried by us for different projectile-target combinations (the projectiles ranging from ^{7}Li to ^{48}Ca) have shown that in all considered cases one can use one and the same set of parameters, *viz.* $r_0 = 1.29$ fm, $V = 67$ MeV, $d = 0.4$ fm [17,20].

The second parameter set defines the competition between the fission and evaporation channels of the formed compound nucleus. These parameters determine the level density in the fission and evaporation channels. In our calculations such parameters were the ratio of the asymptotic values of the level density in the fission and evaporation channels $\tilde{a}_\mathrm{f}/\tilde{a}_\nu$ and the free parameter c in the formula for the fission barrier.

Comparing the calculated and the experimental excitation functions of the fission and evaporation reactions for a wide range of nuclei a conclusion was drawn that in all cases one can use the fixed value of $\tilde{a}_\mathrm{f}/\tilde{a}_\nu = 1$. Moreover, the dependence of the ratio $\mathit{\Gamma}_\mathrm{n}/\mathit{\Gamma}_\mathrm{f}$ on excitation energy, obtained in ^{22}Ne-inducedreactions on ^{194,196,198}Pt [20], has shown that this value of $\tilde{a}_\mathrm{f}/\tilde{a}_\nu$ leads to consistency between experiment and calculations. Therefore, this parameter was also fixed.

The parameter c does not have a fixed value. It changes with Z and A of the compound nucleus. The point is that it changes slowly and, more importantly, smoothly. This allows reliable determination for a definite compound nucleus by extrapolating from the close-by nuclei. For the heavy astatine nuclei the parameter $c = 0.8$.

Thus, in the analysis of the experimental data for the ^{6}He + ^{209}Bi reaction there are no free parameters.

A special attention should be also paid to the quantity ℓ_cr, another parameter of importance in the calculations of the fission cross-section. This is the critical angular momentum that, at high enough energies (when it becomes less than ℓ_max), determines the number of partial waves leading to the formation of the compound nucleus. As the parameters (r_0, d, V, $\tilde{a}_\mathrm{f}/\tilde{a}_\nu$) stay constant in a wide range of nuclei and c varies smoothly with Z and A, one can use for the calculation of the cross-sections of a definite reaction the values from any other reaction leading to the formation of compound nuclei lying close by.

Before analyzing the fission data, obtained in the reaction ^{6}He + ^{209}Bi, it was necessary to perform calculations for the reaction ^{4}He + ^{209}Bi for which a detailed measurement of the fission excitation function, as well as of the 3n, 4n, and 5n evaporation channels [21] exists. The reason for this was that, first, it was necessary to check the validity of the used set of parameters and, second, to carry out a comparative analysis for the two reactions. Such an analysis would help revealing the peculiarities of the ^{6}He + ^{209}Bi reaction, if they exist.

The experimentally measured excitation functions of the reaction ^{4}He + ^{209}Bi for the (α, f)-, (α, 3n)-, (α, 4n)- and (α, 5n)-channels, together with the results of calculations are shown in fig. 2. In the calculations, the only free parameter was ℓ_cr. Agreement between the experimental and calculated fission cross-section in the last point of the excitation function at $E^* = 69.2$ MeV ($E_\mathrm{lab} = 80$ MeV) was obtained for the value of $\ell_\mathrm{cr} = 35$. The good agreement between calculations and experiment showed the possibility to use our approach to calculate reactions induced by such light particles as helium and confirmed the validity of the used set of parameters.

This set of parameters was then used to calculate the fission and 4n evaporation excitation functions for the reaction ^{6}He + ^{209}Bi, which are presented in fig. 3, together

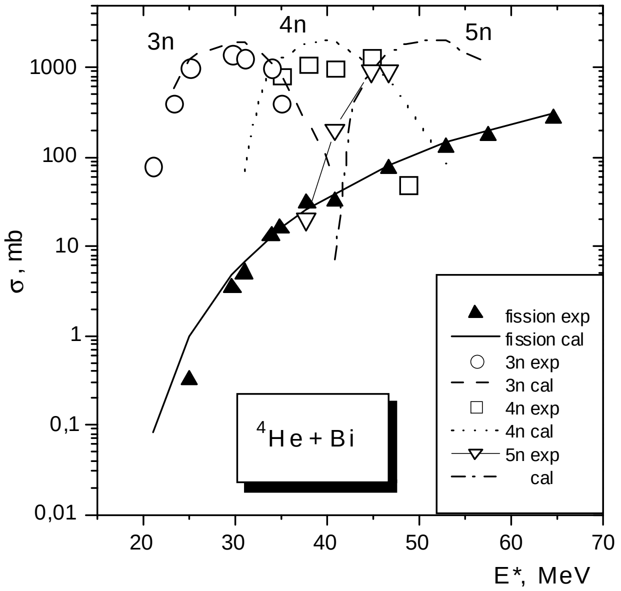

Fig. 2. Excitation functions for the reaction ^{4}He + ^{209}Bi: the symbols denote the experimental data from the present work and from refs. [15,21], the solid, dotted, dash-dotted and dashed lines are the result of calculations.

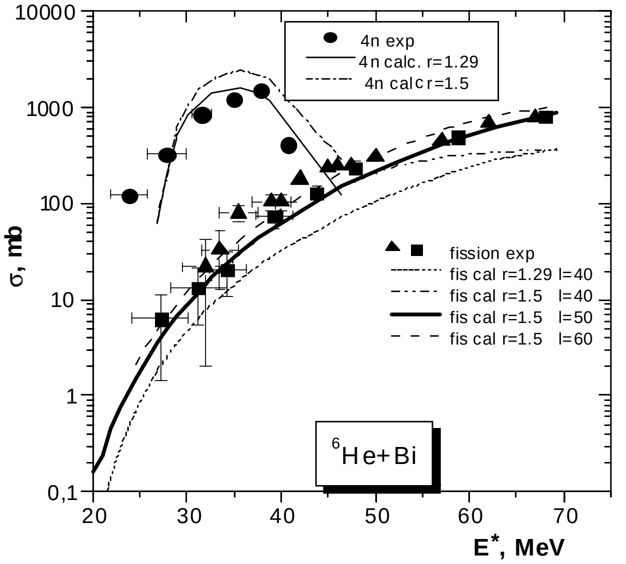

Fig. 3. Excitation functions for the reaction ^{6}He + ^{209}Bi: the black symbols denote the experimental data, the lines, the calculations with different values of r_0 and ℓ_{cr}. For details see the text.

with the experimental data. The solid line denotes the results, obtained with the standard set of parameters. It can be seen that for ^{6}He (in contrast to ^{4}He, for which good agreement was reached when using these parameters) the calculated excitation function is significantly lower than the experimental one, while for the 4n evaporation channel the agreement is satisfactory. Also, the calculated and the experimental fission excitation functions are parallel in the whole energy range and do not converge when increasing the energy.

It is noteworthy that in the calculations the value $\ell_{\mathrm{cr}} = 40$ was used. For the highest excitation energy, $E^* = 70$ MeV, the quantity $\ell_{\max}$ practically coincides with this value. For this reason, it is not possible to improve the agreement by a simple increase of ℓ_{cr} (the increase of ℓ_{cr} to 50 causes σ_{f} to change in the last point by only 15%). Therefore the only way to increase the compound-nucleus formation cross-section, and consequently the fission cross-section, is to decrease the height of the Coulomb barrier. Remaining in the one-dimensional model, this can be achieved by increasing the interaction radius. Indeed, the increase of the value of r_0 to 1.5 fm or 1.6 fm (and ℓ_{cr} to 50) will bring forth complete agreement between the experimental and calculated fission excitation functions. Such an increase in the interaction radius corresponds to decreasing the Coulomb barrier by 15% ($r_0 = 1.5$ fm) or by 20% ($r_0 = 1.6$ fm). In the meantime, the 4n evaporation cross-section changes insignificantly, as it could be expected, since the main contribution to the cross-section of the evaporation reactions for energies not far from the maximum of the excitation function comes from the partial waves with relatively small values of ℓ ($\ell = 30$–35).

It is unlikely that the increase in the interaction radius by 15% (or even 20%), when going from ^{4}He to ^{6}He, could have something to do with the geometrical size of the nucleus ^{6}He. More probably, it is connected with the enhancement of fusion above the barrier, due to the influence of other channels on the fusion process. What are these channels and what is their contribution is a matter of further investigations. However, it seems reasonable to suppose that the pair of weakly bound neutrons in ^{6}He plays here a decisive role.

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References

1. I. Tanihata *et al.*, Phys. Rev. Lett. **55**, 2676 (1985).
2. I. Tanihata *et al.*, Phys. Lett. B **289**, 261 (1992).
3. M.Takigawa *et al.*, Phys. Rev. C **47**, R2470 (1993).
4. C. Dasso *et al.*, Nucl. Phys. A **597**, 473 (1996).
5. M. Hussein *et al.*, Phys. Rev. C **46**, 377 (1992); Nucl. Phys. A **588**, 85c (1995).
6. N.K. Skobelev *et al.*, JINR Rapid Comm. **4**(61), 36 (1993).
7. Yu.E. Penionzhkevich *et al.*, Nucl. Phys. A **588**, 258 (1995); A.S. Fomichev *et al.*, Z. Phys A **351**, 129 (1995).
8. J.J. Kolata *et al.*, Phys. Rev. C **57**, R6 (1998); P.A. De Young *et al.*, Phys. Rev. C **58**, 3442 (1998).
9. J.J. Kolata *et al.*, Phys. Rev. Lett. **81**, 4580 (1998).
10. M. Trotta *et al.*, Phys. Rev. Lett. **84**, 2342 (2000).
11. A. Yoshida *et al.*, Phys. Lett. B **389**, 457 (1996).
12. K.E. Zyromski *et al.*, Phys. Rev. C **55**, R562 (1997).
13. C. Signorini *et al.*, Nuovo Cimento A **111**, 917 (1998).
14. A.S. Fomichev *et al.*, JINR Rapid Comm. **4**(67), 21 (1994).

15. A.V. Ignatyuk, M.G. Itkis *et al.*, Yad. Fiz. **40**, 625 (1984) (in Russian).
16. S.M. Lukyanov *et al.*, JINR Communication P13-2000-283, Dubna 2000.
17. Yu.A. Muzychka, B.I. Pustylnik, *Proceedings of the International School-Seminar on Heavy-ion Physics, Alushta, 1983* (JINR Publ. Dept. D7-83-644, Dubna, 1983) p. 420.
18. A.V. Ignatyuk, G.N. Smirenkin, A.S. Tishin, Yad. Fiz. **21**, 485 (1975) (in Russian).
19. S Cohen, F. Plasil, W.J. Swiatecki, Ann. Phys. (N.Y.) **82**, 557 (1974).
20. A.N. Andreev *et al.*, Nucl. Phys. A **620**, 229 (1997).
21. S.S. Rattan *et al.*, Radiochim. Acta **55**, 7 (1991).