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STUDY OF THE ^{4}He+^{209}Bi FUSION REACTION

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1. INTRODUCTION

The study of nuclear reactions involving weakly-bound or radioactive nuclei is one of the most challenging experimental and theoretical problems in nuclear physics. It is well established that the coupling of collective degrees of freedom to the fusion channel enhances significantly the tunneling probability at sub-barrier energies [1]. On the other hand, the low binding energy of radioactive nuclei may cause important loss of incoming flux due to the breakup process. If the breakup of the nucleus occurs at large distances from the barrier, we may expect an incoherent competition between breakup and fusion and a consequent inhibition of the Complete Fusion (CF) cross section. If, on the other hand, the breakup occurs in such a condition that both fragments have time to interact with the target, a coherent coupling of breakup to the fusion channel may enhance the fusion cross section, and an increase of Incomplete Fusion (ICF) yield may occur. Theoretical calculations, based on Continuum Discretised Coupled Channel (CDCC), predict a suppression of the CF yield at energies above the Barrier, and an enhancement at sub-barrier energies [2]. In order to quantify the modification on the fusion yield, it has to be compared (experimentally or theoretically) to a specific reference. Two problems arise in this case. First the choice of the reference (which has to be the same experimental and theoretically), and second, the use of an unambiguous definition of the Complete Fusion yield.

In this paper we report on the cross section for the evaporation residues yields (xn channels) produced by the fusion of ^{4}He+^{209}Bi, for beam energies between 20.7-55 MeV. Precise measurements of the fusion cross section for the ^{4}He on ^{209}Bi are very important to study the effects of nuclear "skin "(and halo) on the fusion process. This reaction, with stable and strongly bound projectile, can be used as a reference in the investigation of the fusion process of the more exotic ^{6,8}He nuclei on ^{209}Bi targets. The fusion of ^{6}He with ^{209}Bi has recently been studied [3] at the Flerov Laboratory for Nuclear Reactions in Dubna, Russia. The neutron evaporation cross sections from the ^{213}At compound nucleus were measured by means of the identification of the delayed α-activity off-line.

2. EXPERIMENTAL PROCEDURE

The ^{4}He beam was produced by the U200M accelerator at FLNR, JINR, with intensity of 10^{11} pps. The bismuth targets were irradiated by ^{4}He beam as shown in Fig. 1. The bismuth metal targets were evaporated onto aluminum foils of 5μm thickness. To vary the energy of the primary beam in the interval 20-55 MeV, we use energy degraders placed between the Bi-targets.

Special "sandwich-type" piles from bismuth targets with thickness 0.5 mg/cm^2 and aluminum degraders were manufactured and irradiated by ^{4}He beam for one hour. Then, the targets were separated and placed in a low background α-spectrometer to count the yield of α-particles. The activity of these targets was simultaneously measured by semiconductor detectors with resolution for α-particles about 100 KeV. The detecting time was longer than a few periods $T_{1/2}$ (^{211}At).

The energies of the incident alpha particles on a specific target were determined by the energy loss into the aluminum degraders placed just before it. The aluminum degraders were 40±4 mg/cm^2 thick. So, as an example, an incident alpha ion beam with 60 MeV in a given degrader would come out with the energy of 55±0.7 MeV (the code LISE [4] was used to estimate the energy loss). The resulting energy straggling (S) of the out coming alpha ion beam from the degrader was considered S ~ 1.2%.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Identification of the evaporation channels from the ^{4}He+^{209}Bi-reaction

The residual nuclei produced in this reaction are short-lived α-particle emitters due to the N=126 and Z=82 closed shell. Main α-decay modes of the nuclei, which can be formed in our case in the ^{4}He-induced reaction, are shown in Table 1 [5].

Table 1 α-decay characteristics of the nuclei, formed in the ^{4}He + ^{209}Bi → $^{213\text{-}xn}$At reaction

xn-evaporation channel	Evaporation residue	$T_{1/2}$	E_α (MeV)
2*n*	**^{211}At**	**7.21 h**	**5.87** **7.28 (^{211}Po 516 ms)**
3*n*	**^{210}At**	**8.3 h**	**5.36 - 5.5** **5.3 (^{210}Po 138.4d)**
4*n*	**^{209}At**	**5.4 h**	**5.647-5.116**
5*n*	**^{208}At**	**1.63h**	**5.751**

The α-particle energy spectrum was measured as shown in Fig. 2. This figure shows the 2n evaporation channel ^{211}At decays by the emission of 5.88-MeV α-particle (41.8 %) and by electron capture (58.2 %) to 0.52-sec ^{211}Po which decays mainly by emitting 7.45-MeV α-particles. The 3n evaporation channel ^{210}At decays by emission 5.36 MeV α-particle. The branching ratio of the alpha particles to the electron-capture is only 0.18% [5]. The electron capture of ^{210}At gives 138.4-day ^{210}Po which decays by emitting 5.3 MeV α-particle. Because of this long half-life,

^{210}Po is only a minor fraction of the total alpha activity during the first several hours after bombardment.

To confirm the xn identification, we measured the half-time decay characteristic curve for this reaction. The results of the α-decay measurement are shown in Fig. 3. We found the half-life of $^{211}At \approx 7.34 \pm 0.04h$, and $^{210}At \approx 8.44 \pm 0.079h$. These values are in a good agreement with the values from Ref. [5].

3.2 Fusion excitation function for the (^{4}He+ ^{209}Bi) reaction

The (^{4}He,xn) cross section on ^{209}Bi was determined by measuring the activity of the residual nuclei. At each bombarding energy, the (^{4}He,2n) cross section was calculated from the alpha–activity multiplied by the branching ratio for the ^{211}At and ^{211}Po formation. The major contribution (> 98%) of the alpha activity originated by the 2n evaporation residue was due to the 7.44-MeV alpha particles of ^{211}Po and 5.86-MeV alpha particles of ^{211}At. At bombarding energies below the threshold for the (^{4}He,3n) channel, the observed alpha-decay activity gave an average half-life for ^{211}Po of 7.34±0.04 hours. This value is in good agreement with previous half-life determination of ^{211}At and was used in making the decay correction.

At higher bombarding energies, alpha-decay particles from ^{210}At were observed. After the ^{210}At and ^{211}At activities had decayed for 5-day, the samples were recounted for ^{210}Po content. As previously mentioned, ^{210}At decays mainly by electron capture (99.82%) to ^{210}Po. The quantitative assay of ^{210}Po is very simple and the corresponding (^{4}He,3n) reaction cross section was calculated with the assumption that all of the ^{210}Po was formed by the electron capture of ^{210}At.

The evaporation residues cross sections obtained for the ^{4}He+^{209}Bi reaction are given in Table 2. We observe that most of the ^{210}Po are produced by the ^{209}Bi (^{4}He,3n)^{210}At reaction at ^{4}He energies greater than 30 MeV. Also, most of the ^{211}Po are produced by the ^{209}Bi (^{4}He,2n)^{211}At reaction at ^{4}He energies close to the Coulomb barrier. The excitation function of the (^{4}He,2n), (^{4}He,3n), and (^{4}He,4n) are shown in fig. 4.

Table 2 Experimental values obtained (in mb) for the cross sections of the ^{209}Bi (^{4}He , xn) reaction at various ^{4}He bombarding energies.

E_{lab} (MeV)	(^{4}He,2n) ^{211}At	(^{4}He,3n) ^{210}At	(^{4}He,4n) ^{209}At
22.7	42		
23.2	113		
23.7	205		
26.76	572.76		
29.82	650.5		
30.84		80	
32.87	906.5		
33.2		400	
34.9	335.4	1000	
39.7		1400	
41		1300	
44		1000	
45		400	820
47.96			1100
51			1000
55			1300

4 . RESULTS

Model calculations for fusion cross sections of similar systems are available in the literature. For instance, Hagino et al [6] as well as Diaz-Torres et al [7] discussed the influence of the breakup on the fusion channel, (based on CC calculations) for the (^{11}Be+^{208}Pb) and (^{6,7}Li + ^{209}Bi) systems respectively. It has been observed that, at sub-barrier energies, a clear enhancement occurs in the fusion yield caused by the breakup. A clear anti-correlation between the magnitude of the enhancement and the binding energy is observed. Coupled Channel Calculations, which do not take into account explicitly the breakup channel are presented in the literature for the ^{4,6}He + ^{209}Bi systems.[8] indicating that, when weakly bound nuclei are involved, the real part of the optical potential, generated by a double-folding procedure, has to be reduced, simulating a loss of the entrance channel flux.

On the other hand, a totally parameter-free approach to describe the fusion process was proposed recently [9]. The calculations were performed using a model for the nuclear interaction that takes into account the effects of the Pauli nonlocality. This interaction has also been successfully used in the description of the heavy-ion elastic and inelastic scattering for several systems in a wide energy range [10,11] and can be used as a reference for one barrier penetration calculations (1BPC).

Within the nonlocal model, the nuclear interaction is connected with the folding potential through:

$$V_N(R) = V_F(R)\, e^{-4\mathrm{v}^2/c^2},$$

where c is the speed of light and v is the local relative velocity between the two nuclei:

$$\mathbf{v}^2 = \frac{2}{\mu}\left[E - V_N(R) - V_C(R)\right].$$

The folding potential depends on the densities of the nuclei. Thus, with the aim of providing a parameter-free description of the nuclear interaction, and consequently a reliable comparison between similar systems, an extensive systematization of the nuclear densities has been proposed [11]. Using this systematics, the parameter-free nonlocal interaction was tested in the description of an extensive fusion cross section data set for 165 different systems [9]. The model provides very good predictions for the fusion of light heavy-ion systems in the context of the barrier penetration models.

We have applied the nonlocal model in the present case of He + ^{209}Bi systems. A Fermi distribution with parameters according to the systematics of Ref. [12] was assumed for the target density. The density distribution drawn from electron scattering for ^{4}He, and depicted in Fig. 5, provides a good prediction for the fusion of ^{4}He + ^{209}Bi (see Fig.5). The sub-barrier energy region is dominated by the 1n evaporation channel which has not been measured in the present work. However the cross section for the (^{4}He, 1n) has been measured by Barnett and Lilley [12] and are shown in Fig.6. The quality of the theoretical fits to the experimental cross section for complete fusion indicates that no coupling of specific reaction channel is required. The nuclear matter density distribution obtained for ^{4}He displays a relatively tight and space constricted matter distribution described by a much smaller diffuseness when compared to other He isotopes as well as other stable isotopes.

Calculations for the ^{4}He + ^{209}Bi, based on a bare potential barrier penetration, as a reference, can be extended to predict the fusion cross section for the ^{6,8}He + ^{209}Bi systems. Within this scenario, we calculate the fusion cross section, for the case of ^{6}He, using two models for the corresponding density (see Fig. 5): i) Fermi distribution according to Ref. [11] and ii) symmetrized Fermi distribution extracted from scattering experiments of proton on ^{6}He [13]. Both distribution provide similar predictions for the fusion cross section of the ^{6}He + ^{209}Bi system (see Fig. 7). Using these cross section calculations as a reference, we compare them to the existing fusion data (see Fig. 8). Initially we compare them to our experimental results for the partial excitation functions of evaporation residues from the ^{213}At compound nucleus to the ^{209}Bi (^{6}He, 4n) ^{211}At cross section. To turn this comparison more significant, Fig. 8 presents the data as a function of the CN excitation energy E*. Data for the ^{209}Bi (^{6}He, 3n) ^{212}At available in the literature [14] are shown in Fig.8 as

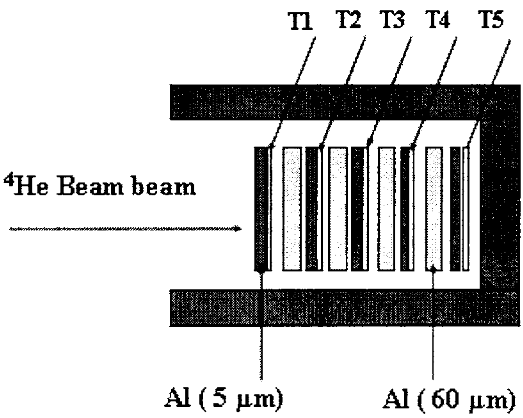

Fig.1: Diagram of the experimental setup, showing the arrangement of Bi targets and energy degraders (Al 5μm and Al 60 μm) between the targets.

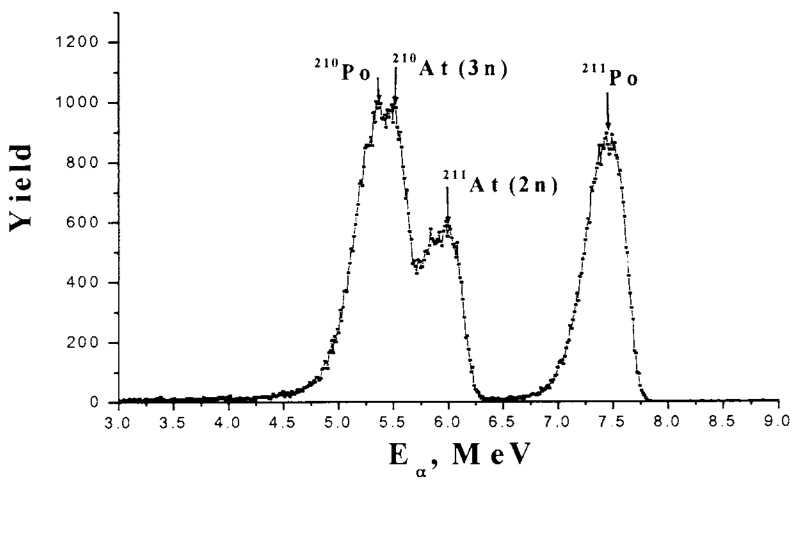

Fig. 2: α-particle energy spectrum for the evaporation residuals in the reaction ($^4He + ^{209}Bi \rightarrow ^{213-xn}At$).

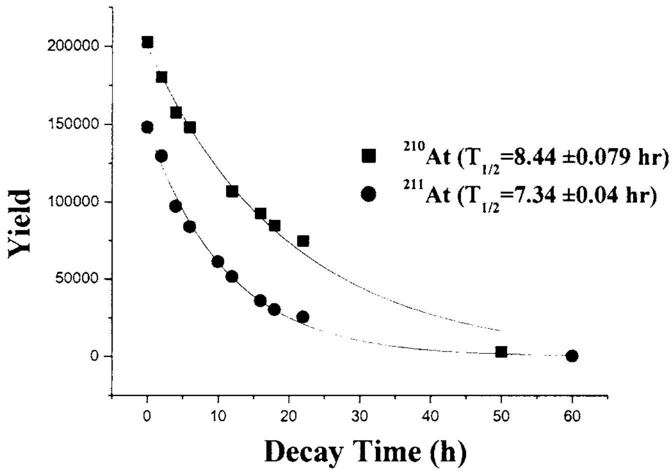

Fig.3: The decay curves of the alpha activity of the evaporation residues ^{211}At and ^{210}At .

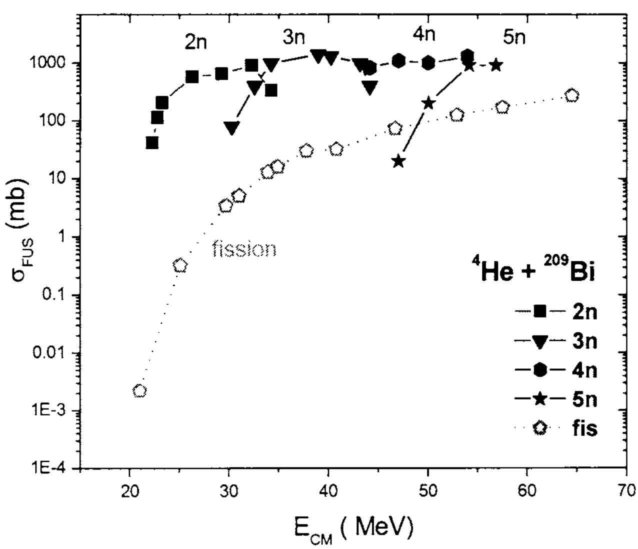

Fig.4: Experimental excitation function for the ^{209}Bi (^{4}He, xn) reaction. The 5n and fission channels [15] are also included. The lines represent guides to the eyes.

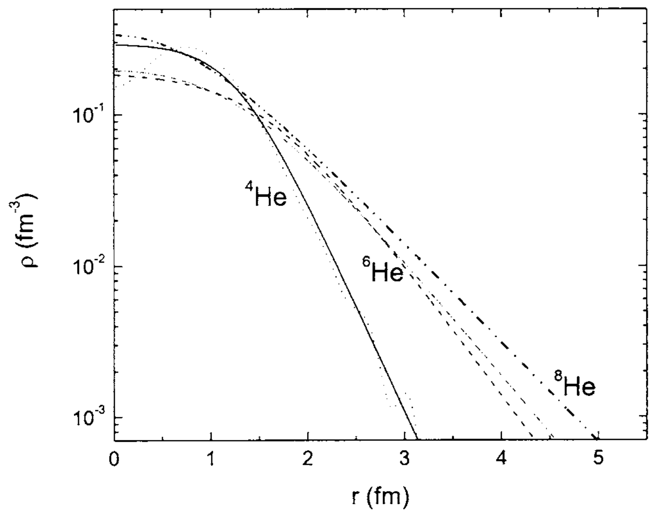

Fig.5: Nuclear matter densities used in the fusion cross section calculations:

a) (dot)-density distribution extracted from electron scattering on ^{4}He nuclei.
b) (solid)-density distribution extracted from proton scattering on ^{4}He nuclei.
c) (dash)-density distribution for ^{6}He obtained from systematic [10]
d) (dash-dot)-density distribution obtained from proton scattering on ^{6}He nuclei.
e) (dash-dot-dot)-density distribution for ^{8}He nuclei extracted from systematic [10].

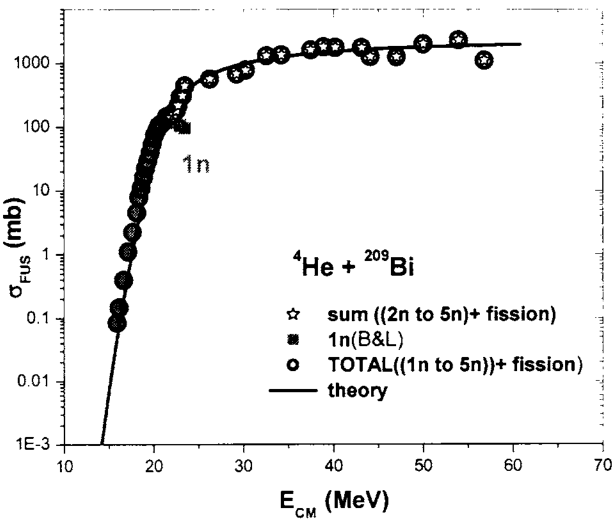

Fig.6: Experimental excitation function for the ^{4}He+^{209}Bi total fusion cross section. The 1n channel was extracted from [12]. Stars represent the sum of the (2n+3n+4n+5n+fission) channels. The open circles include the 1n cross section. The curve represents the predictions based on the parameter free calculations [9,11]

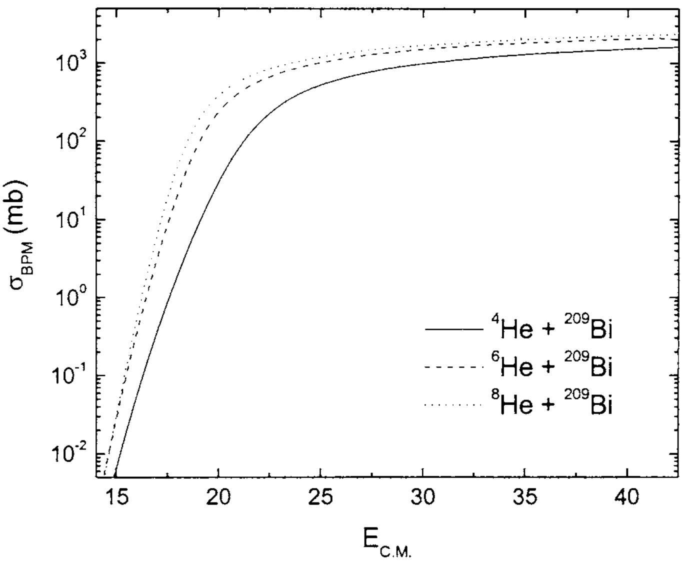

Fig.7: Theoretical predictions for the $^{4,6,8}He + ^{209}Bi$ fusion reaction based on nuclear mater densities depicted in Fig.5, without the explicit inclusion of the coupling to breakup channels.

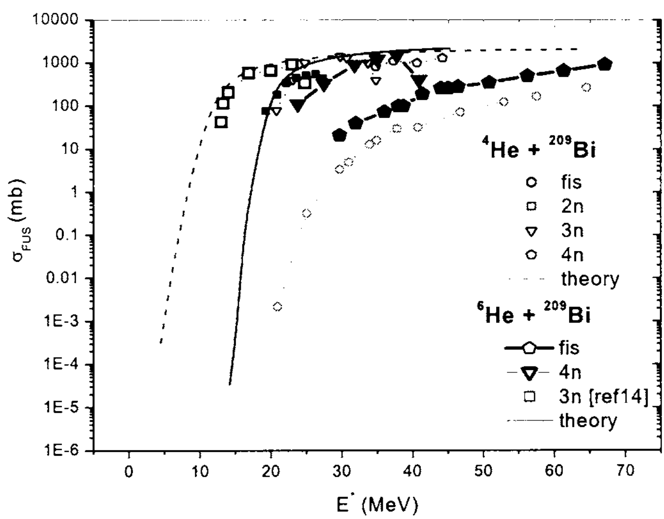

Fig.8: Experimental excitation function for the ^{209}Bi (^4He, xn) reaction (open symbols), as a function of the CN excitation energy. The $^{209}Bi(^6He,3n)$ yields [14] are represented by the solid squares and the ^{209}Bi (^4He, 4n) yields are represented by the solid triangles. The theoretical calculations for the fusion cross section for both systems are represented by the dashed line ($^4He + ^{209}Bi$) and solid line ($^6He + ^{209}Bi$).

well as theoretical predictions for fusion cross section for both reactions (^{4,6}He + ^{209}Bi). It is clear that the available data for the ^{6}He induced reaction are insufficient to draw any reliable interpretation. However these data may suggest some slight trends. Within the experimental uncertainties, the available data for ^{6}He suggests an enhancement tendency of the cross section at sub-barrier energies which may be quantified with the measurement of the ^{209}Bi (^{6}He, 2n) channel. Above the barrier a slight suppression may be quantified by measuring the ^{209}Bi (^{6}He, 5n) channel. These discrepancies to the 1BPM could be related to the influence of the break-up channel [6].

5 . CONCLUSIONS AND PERSPECTIVES

In conclusion, we measured the excitation function for the evaporation of neutrons emitted following the fusion of ^{4}He+^{209}Bi reaction for ^{4}He beam energies below and near the Coulomb barrier. A good agreement between the experimental measurements and model calculations has been achieved using a model for the nuclear interaction that takes into account the effects of the Pauli nonlocality. Very good fits were obtained to theoretical fusion model calculations based on realistic nuclear densities. Precise cross-section measurements at near barrier energies are still required to determine the possible effect of the breakup process. Since, the ^{6,8}He nucleus, with weakly bound neutrons around a ^{4}He core, have a "neutron-skin" structure, we intend to investigate possible enhancement in fusion reaction near and below the coulomb barrier, when induced by ^{6,8}He compared to the fusion reaction induced by ^{4}He on ^{209}Bi target.

Clearly, the available data in the literature for ^{6}He induced reactions are not sufficient to draw any firm conclusion about a possible sub/(above) -barrier enhancement/suppression and the measurement of the (^{6}He,2n and 5n) decay-channels are important in the determination dynamics of the collision.

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Хассан А. А. и др. E15-2003-186
Исследование реакции слияния $^{4}He + ^{209}Bi$

Реакция слияния ($^{4}He + ^{209}Bi$) исследовалась при энергии вблизи кулоновского барьера. Эксперимент проводился на выведенном пучке ионов ^{4}He ускорителя У200 (ЛЯР ОИЯИ). Были получены функции возбуждения для испарительных каналов $2n$, $3n$ и $4n$ реакции $^{209}Bi(^{4}He, ^{213-xn}At)$. Идентификация $2n$- и $3n$-каналов осуществлялась на основе периодов полураспада ((7,34 ± 0,04) и (8,44 ± 0,079) ч) и энергии α-частиц, испущенных дочерними ядрами ^{211}At и ^{210}At. Результаты сравниваются с предсказаниями теоретических моделей и с существующими данными для реакции слияния $^{6}He + ^{209}Bi$.

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Hassan A. A. et al. E15-2003-186
Study of the $^{4}He + ^{209}Bi$ Fusion Reaction

The $^{4}He + ^{209}Bi$ fusion reaction has been investigated at energies near and below the Coulomb barrier. The ^{4}He beam was produced by the U200 accelerator (FLNR, JINR). Excitation functions for the $2n$, $3n$ and $4n$ evaporation channels from the ^{213}At compound nucleus were obtained. To identify the $2n$ and $3n$ evaporation channels, α-particle energies were measured for ^{211}At and ^{210}At as well as half-life times of (7.34 ± 0.04) and (8.44 ± 0.079) h, respectively. The results are compared to theoretical fusion models and to existing data for the $^{6}He + ^{209}Bi$ fusion reaction.

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

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